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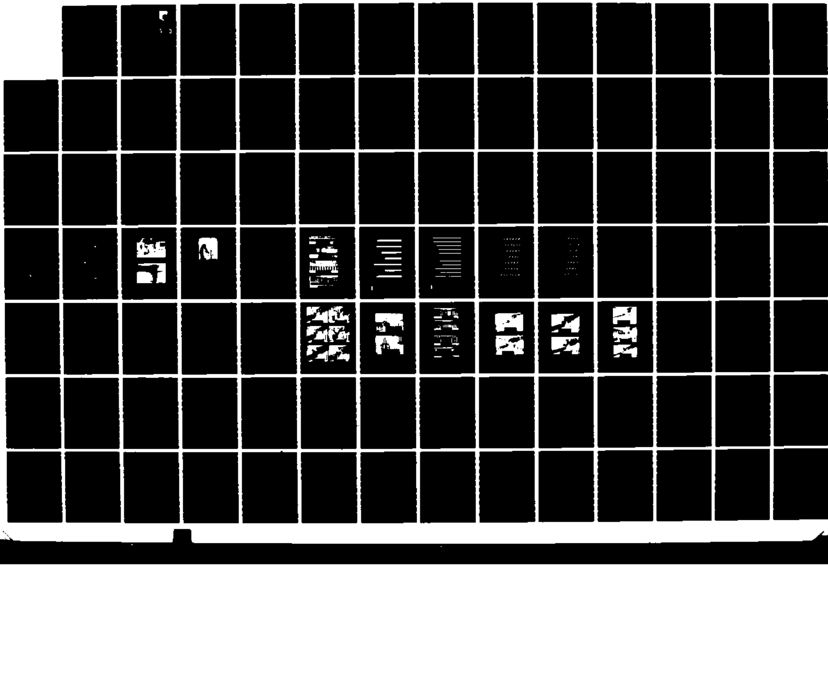

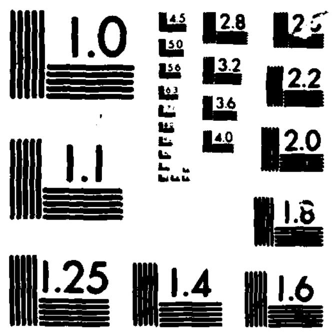

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EVALUATION OF A MULTI-LAYERED
HONEYCOMB SANDWICH CONCEPT FOR USE
IN TRANSPORTABLE SHELTERS

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A concept of combining different honeycomb material types into one sandwich panel was evaluated. Using layers of paper and aluminum or paper and aramid honeycomb in a panel was shown to improve the impact damage resistance as compared to an all paper honeycomb panel. Various combinations of three different core types were evaluated. Specimens were tested for beam shear and compressive strength, drop impact damage resistance, and thermal conductivity. The shear and compressive tests were carried out at both room temperature and 200°F (93°C) while the impact tests and thermal conductivity measurements were conducted only at room temperature. The results demonstrate the advantage of combining layers of ductile, impact resistant core such as aramid or aluminum with low cost paper honeycomb. The impact damage resistance of multiple layered core exceeds that of full depth paper core for typical transportable shelter designs. A cost and weight analysis was conducted which demonstrated that the weight penalty and economics of this approach can be easily justified by the improved service life of shelter structures.

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(U) EVALUATION OF A MULTI-LAYERED HONEYCOMB SANDWICH CONCEPT FOR USE IN TRANSPORTABLE SHELTERS

PREFACE

This report covers work performed during the period from September 1980 to March 1982 under Air Force Contracts F33601-80-C-0312, F33615-82-C-5039, and F33615-84-C-5079. The work was performed by the Hexcel Corporation, evluated by the University of Dayton Research Institute, and administered under the direction of the Systems Support Division of the Air Force Wright Aeronautical Laboratories/Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. John Rhodehamel was the program Project Engineer. The author is indebted to Mr. Robert Askins of the University of Dayton Research Institute for his extensive technical and editorial review of the report.

This report was submitted by the author for publication in January 1985.

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SECTION 1
SUMMARY

This report presents the results of a test program to evaluate sandwich panels which were fabricated using double layers of different types and thicknesses of honeycomb core materials. Combinations of aluminum, aramid, and paper honeycomb were layered and adhesively bonded to aluminum facings. The T-splice joint between the two core layers was made with a woven fiberglass prepreg impregnated with a modified epoxy resin on some panels while on others a film adhesive was used at the T-splice.

The results of this investigation clearly indicate that the impact damage typical of paper honeycomb core is greatly reduced with the double layer sandwich concept. Both aluminum and aramid core crush locally rather than shattering in a brittle failure mode. Because of the reduced damage, structural integrity is not greatly reduced and subsequent repair techniques are much simpler. Beam shear tests indicate that the double core shear strengths generally fall between the strength levels of the individual core types used. Thus, a two inch thick double layer panel made with one-inch aluminum and one-inch paper core exhibits a shear strength between that of a single two-inch aluminum and two-inch paper honeycomb panel. Thermal conductivity of a double-layer core likewise falls between that of the two individual core types.

Compressive properties of multi-layered sandwich panels were lower than those of either core alone. This was determined to be caused by the inability of the single ply splice layer to provide sufficiently stable cell edge support and prevent the sharp core cell edges from cutting into and through the splice.

A subsequent investigation was carried out in which a rigid core splice layer was substituted for the single ply non-rigid splice layer. The results are presented in Appendix B. They

indicate that the use of a rigid splice layer not only overcomes the problem of decreased compressive properties in multilayered sandwich panels, but also produces higher beam shear properties as well.

Since honeycomb is the major cost item in a sandwich panel, the economics of using paper in combination with aramid honeycomb are shown to be better than an all aramid panel. Similarly, the use of some paper with aluminum core holds cost down while greatly improving the impact resistance.

SECTION 2

INTRODUCTION

Non-metallic honeycomb made of Kraft[1] or Nomex[1] paper coated with phenolic resin has been used in numerous sandwich structures including transportable shelters. The predominant shelter sandwich construction consists of these core types bonded to aluminum facings with elevated temperature curing adhesives. Compared with alternate designs, such as the "foam-and-beam" shelter, a honeycomb sandwich panel offers several advantages, including optimum strength-and-stiffness-to-weight ratio, mount-anywhere capabilities for shelving, racks, etc. using potted fasteners, relative ease of minor repairs, and the toughness of Nomex honeycomb panels. Honeycomb by itself does have higher thermal conductivity, however, this can be improved by filling the core with foam. Kraft paper core such as WRII is relatively brittle and has poorer wet strength than Nomex but in many cases this is offset by the higher cost of Nomex honeycomb.

The MIL-H-43964(GL) specification for non-metallic honeycomb for shelter panels contains a dynamic drop test requirement which is difficult or impossible to meet with the currently available Kraft paper-based core types. The test involves dropping a sixty-seven pound weight onto a test panel in which the core is allowed to crush locally but not shatter or fracture (ref. 1). Honeycomb cores made of aramid paper (Nomex) or aluminum pass this requirement. The latter has high heat transfer properties, however. Thus, each core type has some good as well as undesirable characteristics.

The objective of this program was to investigate and test the concept of combining several different core types into one sandwich panel, taking advantage of the best properties each core has to offer (see Figure 1).

A typical panel thickness for shelters is about two inches. This is also the test thickness used in MIL-H-43964. Hence,

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[1]Trademark, E. I. DuPont DeNemours Co.

while this study used two inches for the basic panel thickness, two additional panel thicknesses (1.5 and 1.0 inch) were included for comparison.

Various combinations of Kraft paper, Nomex, and aluminum honeycomb core were fabricated into sandwich panels and each core type was also used individually. Thus, two inch thick full-depth panels, consisting of two one-inch layers, and panels consisting of a 0.5 inch and a 1.5 inch layer were all compared.

SECTION 3

PROCEDURE

3.1 MATERIALS

Three different types of honeycomb were included in this study

WRII	-	Kraft Paper Based, Phenolic Resin Dipped. This core type is used extensively in military shelters, has good shear and compressive properties, and is low in cost.
HRH10	-	Aramid Paper Based, Phenolic Resin Dipped. This core is used in various aircraft structures. It is extremely resilient and has good dry and wet strength; it is more expensive. (HRH78 is a commercial version.)
Aluminum-		Available in four different alloys. 5052 and 3003 were used in this program. Aluminum core is ductile, relatively low in cost and used in numerous structural applications.

Transportable shelter structures in the past have used higher strength materials for floors and walls, and lower strength cores in some roof and folding panels. Thus, it was decided to include honeycombs of two different strength levels. WRII is available in two densities -- 2.5 and 3.8 pounds per cubic foot. Low and high density aluminum and Nomex cores were selected with similar strengths to the WRII.

The following six core types were used. Note that the letter designation will be used frequently in this report for quick reference.

A	Aluminum	ACG-3/8-3.6
B	Aluminum	5052-1/4-4.3
C	Kraft Paper	WRII-3/8-2.5
D	Kraft Paper	WRII-3/8-3.8
E	Aramid Paper	HRH-10-3/8-3.0
F	Aramid paper	HRH-10-1/4-4.8

Two-inch panels were made with each of the above core types to serve as the basis for property correlation. Then combinations of 0.5, 1.0, and 1.5 inch thick cores were made into the multilayered sandwich panels. Table 1 describes these combinations.

The facings for all panels were .040 inch thick 5052 H34 aluminum. Just before bonding, the facings were cleaned and etched with the standard FPL treatment. The adhesive used to bond core and facings was Hysol's EA9601 NW at 15 mil thickness. The T plane splice (between honeycomb layers) was made with one ply of Hexcel's F185 prepreg on 7781 woven fiberglass for most of the specimens. This material is normally used to make laminates and has a matrix resin which bonds well to various core types. Some of the specimens, as will be noted in a subsequent section, were remade with a film adhesive (Hysol's EA9601NW) as the T-plane splice rather than the F185 prepreg.

In addition to the types of specimens described above, a small followup investigation was carried out in which a rigid aluminum sheet was used as the splice plane layer rather than a single ply of prepreg or adhesive film alone. These results are described in Appendix B.

The assemblies were co-cured in a heated platen press at 260°F for one hour under a pressure of about 20 psi. In order to obtain the required number of test specimens, 24 x 24 inch and 13 x 18 inch panels were made. Table 2 itemizes these various panels and also lists the panel weights. Beam flexure and compressive specimens were band-sawed from the panels and prepared for testing. The thermal conductivity specimens were spliced with a F185 glass prepreg, but no facings were bonded to these 12 x 12 inch core sections.

3.2 TESTING

Four types of tests were conducted:

a) Beam flexure (L and W directions) at ambient and 200°F,

b) Thermal conductivity,

c) Drop impact, and

d) Stabilized compression at ambient and 200°F.

Not all tests were conducted for every panel type. Ambient compression and beam flexure tests were conducted on all panels but the 200°F tests were carried out with only a few panel types. The thermal conductivity tests were omitted for the two inch thick aluminum because of instrument limitations.

The compression specimens were 3 x 3 inches and tested in accordance with MIL-STD-401B. The beam flexure specimens were loaded through a single center bar 3 inches wide with 1.5 inch wide support pads and a span of 14 inches. Figure 2 illustrates this specimen. Load-deflection curves were obtained for the ambient tests. The loading rate for these tests was 0.05 inches per minute to failure. The 200°F tests were conducted the same way inside a test oven after 10 minutes exposure. The beam flexure specimens were examined for type of failure and the data converted from load at failure to core shear strength. The formula for this is $\tau = \frac{P}{2(d-t_f)b}$

where: τ = core shear strength in psi

P = load at failure in pounds

d = sandwich thickness in inches

t_f = facing thickness

b = specimen width

The thermal conductivity coefficients (K) were obtained with a K-Matic heat flow meter (Figure 3). This instrument measures K at a mean temperature of 75°F using a 12 x 12 inch specimen size. The panels which had aluminum core were tested both ways, with the aluminum core up and down.

The impact tests were conducted with the "Trifel Tower" illustrated in Figure 4. The test consists of dropping a 67 pound weight with a three inch diameter spherical head onto a 24

x 24 inch panel. The drop height was 30 inches for the heavier density core types and 20 inches for the lighter panels. After the test, the panels were cut through the impact area and examined for type of failure.

SECTION 4
DISCUSSION OF RESULTS

The physical and mechanical properties measured in this program indicate that the concept of using two (or possibly more) layers of honeycomb in one sandwich panel could offer some interesting advantages. One major concern in the transportable shelter industry has been the rather brittle nature of Kraft paper based honeycomb and the higher relative cost of the very resilient aramid paper based cores. This program demonstrates that it is possible to combine the best of both materials.

4.1 WEIGHT ANALYSIS

Figure 5 illustrates the weight distribution of two typical double layer sandwich panels; one with 2.5 pcf honeycomb, the other with 5.0 pcf core. It is evident that the splice does not contribute a large portion of the panel weight. Most of the panel weight comes from the facings and honeycomb. Table 3 lists the panel weights for all the combinations which were fabricated for this investigation. It is apparent that the major variations in weight are due to the density of the particular type of honeycomb core or cores in the panel.

4.2 BEAM FLEXURE RESULTS

The beam flexure tests were designed to prevent compressive type failures under the loading pad. This was to have been accomplished by using a rubber pad under the three-inch wide loading bar. In spite of this, not all of the failures were good core shear failures. Compressive failures did occur with some high density L direction specimens, but not until after good shear buckling lines were observed in the honeycomb. In other words, shear failure was imminent when the top facing buckled into the core. Hence, the load at failure was fairly representative of the core's shear capability.

In addition to the compressive failures described above, some of the beam flexure specimens failed in the splice by delamination. This splice joint must provide sufficient bond strength to the honeycomb to carry the shear stresses as well as provide support for the compressive forces encountered. Apparently, the low resin content of the laminating grade prepreg (Hexcel's F185) was insufficient to form good fillets. Figure 6 shows four typical failed beam flexure specimens. Three of the panels exhibited good shear failures while one exhibits delamination in the splice. The lack of resin and fillets are quite noticeable at the broken splice line. Because of the behavior of the panels with this resin starved splice, another series of panels with the same core combinations was made using EA9601NW film adhesive as the splicing material. These panels proved better and did not fail in the splice area at room temperature. Figures 7 and 8 and Tables 4-7 summarize the beam flexure shear test results.

At 200°F, however, the splice was again the weak link. The strength values obtained for the double sandwich panels in shear were all much lower than anticipated because of splice failures. These results are presented in Table 8. Most of the full depth honeycomb beams failed in shear at both room temperature and 200°F so the effect of temperature can be correlated. The data indicates that aluminum honeycomb retains about 92% of its RT strength at 200°F; WRII retains 49%, and HRH-10 retains 84%. These data illustrate one of the superior characteristics of the aluminum and Nomex honeycomb over the WRII.

Keeping in mind that some differences in mode of failure are included, the data does indicate that the shear strengths of the double layer sandwich panels fall between the strengths of the two core types used. For example, series 8AC, which combines aluminum and WRII core, has shear strength about half way between that for aluminum and WRII honeycomb.

Since the shear stesses are uniform through the core thickness of a sandwich panel, one would expect these panels to be only as strong as the weakest core section. The fact that the multi-layered panels had shear strengths higher than the weakest core type would suggest that there could be a thickness effect. Indeed, it is well known that honeycomb has higher shear strengths as the thickness is decreased (Ref 2 and 4). Thus, the additional benefit of higher shear properties due to use of thin slices was realized to some degree with the multi-layered panel approach.

Figures 9 through 15 illustrate the deflection of the sandwich flexure beams at the center point when the load reached 500 lbs. for the low density core types and 1,000 lbs. for the high density core panels. These deflections were obtained from the individual load-deflection curves presented in Appendix A. Of course, the smaller the deflection, the stiffer the panel. In all these cases, the deflections followed a pattern of being high for HRH-10 and WRII and low for aluminum core. The larger the amount of aluminum core which is used, the lower the deflection. The one anomaly was the W direction beams for series 10BD.

Thus, it has been demonstrated that it is possible to select a combination of core materials which will provide the sandwich panel with better stiffness than that which can be obtained from an all non-metallic honeycomb at the same density and thickness.

4.3 THERMAL CONDUCTIVITY RESULTS

The thermal conductivity values, K, are presented in Table 9 and illustrated in Figures 16-19. The aluminum core is a good conductor, and no data could be obtained on the full depth aluminum panels. Panels made with combinations of aluminum and either WRII or HRH-10 core were tested in both orientations, aluminum layer up and down. Indications are that this made only a slight difference. Figures 17 and 19 show this more clearly. Figure 16 presents the thermal conductivity values for the HRH-10

and WRII core. Previous tests of these types of materials have shown that smaller cell size and lower density provides better insulation (ref. 3). The results obtained here corroborate those trends. A 1/4 inch cell size in HRH-10 gave a lower conductivity than a 3/8 inch cell size in spite of a higher density. For a 3/8 inch cell size in WRII, the lower density gave a lower conductivity than the higher density.

Additional testing was done with the above specimens after filling the cells of the non-metallic core types with a friable phenolic foam. The reduction in thermal conductivity values are shown in Figures 18 and 19.

4.4 IMPACT RESULTS

The impact tests, performed as shown in Figure 4, were probably the most interesting part of this program. The type of failure where the core crushes under the impact area is desirable since that type of failure can be repaired easily by filling the dented facing. This type failure is typical of both aluminum and HRH-10 full-depth honeycomb, as illustrated in Figure 20. If the facing is punctured, delamination occurs, or the core shatters and breaks up, the panel strength may be adversely affected, and the repair is more involved. Figure 21 illustrates the cross-section of two impact damaged WRII panels with full-depth core. The cracked and shattered paper core can be clearly seen.

For double layer sandwich panels made with HRH-10 or aluminum core on top of WRII core, it is shown that while core crushing still occurs in the upper layer, the WRII layer remains essentially intact. Panels which contained only a half-inch thick layer of aluminum or HRH-10 core and which had that layer completely crushed during impact, exhibited only a slight deformation of the splice and WRII layer and no fracture of the WRII core. In the case of panels with a one-inch thick upper layer, only the aluminum or HRH-10 showed evidence of crushing with no damage at all to the splice or WRII layer. Figures 22 through 25

show the cross-sections of the various double-layer specimens tested.

4.5 STABILIZED COMPRESSION RESULTS

Compressive testing was performed on the sandwich panels at both ambient and 200°F. This data is summarized in Tables 10 and 11 and illustrated in Figures 26 and 27. Figure 26 compares the low density core types while Figure 27 compares the higher density core types. It is evident from these figures, that a sharp reduction in room temperature strength occurs with the multi-layered panels incorporating the high density cores. This was due to the inherent weakness of the splice material selected. The sharp edges of the core cut into and through the splice, causing premature failure of the sandwich. In the case of the high density core types this happened at about 400 psi compressive stress. A more rigid splice such as a thin aluminum sheet bonded between the two different core types would probably reduce or eliminate this effect.

The 200°F test data shows this effect again. One would expect the multi-layered panels to fail in compression at a stress close to the weakest core type in the panel. The panel containing HRH 10 and aluminum (15FB) had a strength at 200°F of 242 psi compared with 586 and 547 psi, respectively for the individual core types. This represents a reduction of 56%. Again, the reason was the weak splice and its unstable cell edge support.

One comparison which can have significant impact on shelter design is the elevated temperature data for each core type. Table 11 lists the percent strength retention with respect to ambient strengths (shown in Table 10). Clearly the aluminum and HRH 10 are superior to the WRII. Shelter roof and wall panels, when exposed to desert sun will get quite hot. Hence, the use of the more impact resistant aluminum or Nomex honeycomb as an outer layer has the added benefit of retaining higher compressive strength at elevated temperatures than WRII.

As noted previously, a followup investigation was performed in which specimens were prepared with a rigid splice plane. These results are presented in Appendix B and indicate that with a rigid splice plane, multi-layered sandwich panels exhibit compressive properties equivalent to or higher than that obtained from single-layer full-depth samples.

4.6 COST ANALYSIS

The cost of the raw materials to make a flat sandwich panel are usually more than the labor costs; providing, of course, that the panel is relatively simple and doesn't have fancy inserts, close-outs, or other details cumbersome to include. The cost of a typical two-inch thick panel evaluated in this investigation can vary from 7 to 28 dollars per square foot. The panel with all WRII core is definitely the lowest cost of the various types and combinations tested. Nevertheless, a panel with ACG aluminum core is only about a dollar per square foot more. Despite the fact that a layer of splicing material is included and more material is handled, the actual panel cost for a two-inch WRII/ACG core combination is in the same ball park. Figures 28 and 29 present cost comparisons for sandwich panels having various types of core and core combinations. It can be seen that when Nomex honeycomb is included, the cost increases more rapidly. However, a high-density panel made with a half-inch thick slice of Nomex core and 1.5 inch WRII is only about 75 percent more expensive than an all-WRII 2-inch panel. By comparison, an all-Nomex core panel with high density honeycomb is three and one-half times as expensive as an all-WRII core panel.

It should be noted that the panel costs presented here are based on using the fabrication technique described in this report for typical 4 x 8 foot panels in large quantities. The values are intended for comparison purposes only and are not to be construed as list prices. They were valid when this comparison was originally made at the start of this program in 1980.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

This test program has demonstrated that sandwich panels made with different types of honeycomb in spliced layers can be designed to utilize the best features of each core material type. Since transportable shelters are prone to impact damage from the exterior side, and since brittle core types tend to fracture or shatter during such impact conditions, the addition of a layer of impact resistant core material will shield the more brittle core and will itself be easier to repair.

The combination of WRII and aluminum honeycomb within one sandwich panel adds very little to the cost of the panel, raises the weight by only 5 to 7 percent, and makes a much more damage resistant as well as a stiffer structure. The thermal conductivity of such a panel will be higher, but this can be reduced by adding a lightweight foam to the WRII core.

Alternately, a layer of an aramid paper core such as HRH-10 can be used instead of the aluminum honeycomb in combination with WRII. Nomex honeycomb will crush rather than shatter during a heavy impact; it will retain about 84 percent of its strength at 200°F (as opposed to 49 percent for WRII), and yet will not increase the cost of a shelter by nearly as much as full-depth Nomex honeycomb would.

One significant factor should be noted with regards to the T-plane splice material. It has to have sufficient bond strength to stabilize the two honeycomb surfaces in a compressive load, carry the shear stresses imposed on the core, and have similar or better durability at elevated temperatures and other environmental conditions. The low resin content fiberglass prepreg used in part of this study was not good enough for an actual application. A layer of film adhesive was found to be much better from the standpoint of transferring shear stresses from one core to the other in a multi-layered sandwich panel. In

order to prevent degradation of compression properties in a multi-layered sandwich panel, a rigid T-plane splice layer is necessary to resist cut-through by the sharp cell edges as well as to provide more stable cell edge support.

Since this approach of combining different core materials into one panel appears to have some distinct advantages, it is recommended that future investigations should include factors such as effect of environmental exposure, incorporating a moisture barrier, and a study of panel strength after various degrees of impact damage. In addition, the possibility of using facings other than aluminum and edge members should be considered.

Honeycomb sandwich still offers the lowest weight structural design. The approach described and tested in this program offers designers much more latitude and design versatility. This technique may well be applicable in solving problems encountered with current designs.

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TABLE 1 CORE COMBINATIONS

Panel Series	Core Types	Core Thickness Inch	Description
1A	ACG - 3/8-3.6	2.0	Low density aluminum core
2B	¼ - 5052 - 4.2	2.0	Higher density aluminum core
3C	WRII - 3/8-2.5	2.0	Low density Kraft paper
4D	WRII - 3/8-3.8	2.0	Higher density Kraft paper
5E	HRH-10 - 3/8-3.0	2.0	Low density aramid paper
6F	HRH-10 - ¼-4.8	2.0	Higher density aramid paper
7AC	ACG WRII - 2.5	0.5 1.5	Combinations of aluminum and WRII.
8AC	ACG WRII - 2.5	1.0 1.0	Low and high densities
9BD	5052 WRII - 3.8	0.5 1.5	
10BD	5052 WRII - 3.8	1.0 1.0	
11FD	HRH-10 - 4.8 WRII - 3.8	0.5 1.5	Combinations of HRH-10 and WRII
12FD	HRH-10 - 4.8 WRII - 3.8	1.0 1.0	High density only
13EA	HRH-10 - 3.0 ACG	1.5 0.5	Combinations of HRH-10 and aluminim
14EA	HRH-10 - 3.0 ACG	1.0 1.0	Low and high densities
15FB	HRH-10 - 4.8 5052	1.5 0.5	
16FB	HRH-10 - 4.8 5052	1.0 1.0	
17FB	HRH-10 - 4.8 5052	0.5 1.0	Effect of panel thickness
18FB	HRH-10 - 4.8 5052	0.5 0.5	

TABLE 1. CORE COMBINATIONS - CONTINUED

Panel Series	Core Types	Core Thickness Inch	Description
21A	ACG - 3/8 - 3.6	2 @ 0.5	Combining different thicknesses of aluminum in a panel
23A	" " "	2 @ 1.0	
24B	1/2 - 5052 - 4.2	2 @ 0.5	
26B	" " "	2 @ 1.0	
27C	WRII - 3/8 - 2.5	2 @ 0.5	Combining different thicknesses of WRII in a panel
29C	" " "	2 @ 1.0	
30D	WRII - 3/8 - 3.8	2 @ 0.5	
32D	" " "	2 @ 1.0	
33E	HRH10 - 3/8 - 3.0	2 @ 0.5	Combining different thicknesses of HRH-10 in a panel
35E	" " "	2 @ 1.0	
36F	HRH-10 - 1/2 - 4.8	2 @ 0.5	
38F	" " "	2 @ 1.0	

TABLE 2 PANEL IDENTIFICATION AND WEIGHTS

Weight in psf

Series		Core Types/T	24 x 24 Drop Test -1	24 x 24 Flex +C -2	13L x 18W Flex -3	18L x 13W Flex -4
1A	Basic Cores	A2.0	1.90	1.89	1.85	-
2B		B2.0	2.04	2.03	2.02	-
3C		C2.0	1.68	1.66	1.66	-
4D		D2.0	2.03	2.00	2.01	-
5E		E2.0	1.87	1.88	1.87	-
6F		F2.0	2.12	2.16	2.14	-
7AC	Alum./WRII	A0.5,C1.5	-	-	1.84	1.86
8AC		A1.0,C1.0	-	-	1.87	1.89
9BD		B0.5,D1.5	2.11	2.11	2.11	-
10BD		B1.0,D1.0	2.13	-	2.12	2.13
11FD	HRH/WRII	F0.5,D1.5	2.14	2.15	2.16	-
12FD		F1.0,D1.0	2.16	-	2.17	2.15
13EA	HRH/Alum.	E1.5,A0.5	-	-	1.98	1.98
14EA		E1.0,A1.0	-	-	1.97	1.97
15FB		F1.5,B0.5	2.17	2.18	2.18	-
16FB		F1.0,B1.0	2.20	-	2.18	2.15
17FB	T	F0.5,B1.0	2.01	-	1.99	2.00
18FB		F0.5,B0.5	1.82	-	1.80	1.84

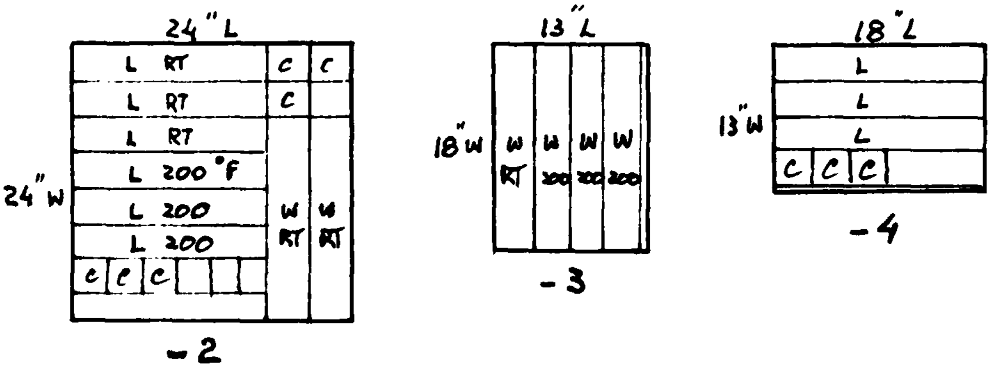


TABLE 3 - PANEL DATA SUMMARY

Panel Series	Core Types	Panel Weight psf	Cost $/sq.ft.	Flexural Load lbs. "L"	Flexural Load lbs. "W"	Comp. Str. psi	Thermal K 2)	Impact Rating 3)
1A	2" Alum.-3/8-3.6	1.88	8.48	1905	1145	280	-	1
2B	2" Alum.-1/4-4.2	2.03	11.42	2950	2281	613	-	1
3C	2" WRII-3/8-2.5	1.67	7.11	1285	651	217	0.83	3
4D	2" WRII-3/8-3.8	2.01	8.06	2422	1523	574	0.87	3
5E	2" HRH10-3/8-3.0	1.87	13.78 1)	2076	1287	221	0.79	1
6F	2" HRH10-1/4-4.8	2.14	28.69	2920	1912	699	0.66	1
7AC	0.5" Alum. 1.5" WRII	1.85	8.29	1299	480	181	0.96	-
8AC	1.0" Alum. 1.0" WRII	1.88	8.65	1539	968	166	1.21	-
9BD	0.5" Alum. 1.5" WRII	2.11	10.03	2175	1734	360	1.04	2
10BD	1.0" Alum. 1.0" WRII	2.12	11.05	2457	2093	350	1.21	1
11FD	0.5" HRH10 1.5" WRII	2.15	14.38	-	1717	391	0.72	2
12FD	1.0" HRH10 1.0" WRII	2.16	19.47	2524	1853	339	0.67	1
13EA	0.5" HRH10 1.5" Alum.	1.98	13.46	1904	1268	180	0.86	-
14EA	1.0" HRH10 1.0" Alum.	1.97	12.18	1843	1216	190	1.04	-
15FB	1.5" HRH10 0.5" Alum.	2.18	25.76	2632	2009	420	0.80	2
16FB	1.0" HRH10 1.0" Alum.	2.18	21.69	2790	2199	427	0.99	2
17FB	0.5" HRH10 1.0" Alum.	2.00	16.01	2401	1715	-	1.14	2
18FB	0.5" HRH10 0.5" Alum.	1.82	14.40	1676	1169	-	0.84	2

1) Cost based on HRH78, the commercial equivalent of HRH10.

2) Coefficient of thermal conductivity in Btu-in./hr.-sq.ft.-F°

3) Impact rating depends on observed mode of failure:

1 = core crushing only
2 = core crush and splice deformation
3 = core shattering

TABLE 4 BEAM FLEXURE FAILURE LOADS AT ROOM TEMPERATURE

Panel Series	L DIRECTION Load-Lbs.	L DIRECTION Type Fail*	W DIRECTION Load-Lbs	W DIRECTION Type Fail*	Panel Series	L DIRECTION Load-Lbs.	L DIRECTION Type Fail*	W DIRECTION Load-Lbs.	W DIRECTION Type Fail*
1A	1891	CS	1109	CS	2B	2880	CC	2277	CS
	1866	CS	1177	CS		3010	CC	2283	CS
Alum	1958	CS	1148	CS	Alum	2960	CC	2264	CS
	1905		1145			2950		2281	
3C	1315	CS	670	CS	4D	2590	CS	1530	CS
	1250	CS	670	CS		2201	CS	1291	CS
WRII	1290	CS	614	CS		2476	CS	1747	CS
	1285		651			2422		1523	
5E	2068	CS	1280	CS	6F	2820	CC	1964	CS
	2074	CS	1392	CS		2950	CC	1935	CS
HRH10	2086	CS	1188	CS	HRH10	2990	CC	1837	CS
	2076		1287			2920		1912	
7AC	1293	CS	569	SD	9BD	2107	SD	1699	CS
	1284	CS	402	SD		2242	SD	1765	CS
Alum/WRII	1320	CS	470	SD	Alum/WRII	NT	-	1737	CS
	1299		480			2175?		1734	
8AC	1543	CS	974	CS	10BD	2470	SD	2074	CS
	1529	CS	975	CS		2492	SD	2054	CS
Alum/WRII	1546	SD	955	CS	Alum/WRII	2460	CS	2152	CS
	1539		968			2457		2093	

*) CS - Core Shear SD - Splice Delamination CC - Core compression under load pad

TABLE 4 BEAM FLEXURE FAILURE LOADS AT ROOM TEMPERATURE - CONTINUED

Panel Series	L DIRECTION		W DIRECTION		Panel Series	L DIRECTION		W DIRECTION	
	Load-Lbs.	Type Fail*	Load-Lbs	Type Fail*		Load-Lbs.	Type Fail*	Load-Lbs.	Type Fail*
13EA	1951	CS	1239	CS	15FB	2627	CC	2016	SD
	1890	CS	1330	CS		2595	CC	1951	SD
HRH10/A1	1871	CS	1236	CS	HRH10/A1	2675	CC	2061	CC
	1904		1268			2632		2009	
14EA	1881	CS	1210	CS	16FB	2800	CC	2228	CS
HRH10/A1	1782	CS	1204	CS		2759	CC	2226	CS
	1866	CS	1233	CS	HRH10/A1	2810	CC	2142	CS
	1843		1216			2790		2199	
11FD	NT	-	NT	-	17FB	2393	CS	1724	CS
	NT	-	1659	CS		2401	CS	1716	CS
HRH10/WRII	NT	-	1775	CS	HRH10/A1	2408	CS	1705	CS
			1717			2401		1715	
12FD	2460	CS	1941	CC	18FB	1665	CC	1172	CS
	2600	CS	1738	SD		1689	CC	1150	CS
HRH10/WRII	2513	CC	1879	SD	HRH10/A1	1673	CC	1184	CS
	2524		1853			1676		1169	

*) CS - Core Shear SD - Splice Delamination CC - Core compression under load peel

TABLE 5

BEAM FLEXURE FAILURE LOADS - ALUMINUM CORE ONLY

Panel Series	L DIRECTION		W DIRECTION		Panel Series	L DIRECTION		W DIRECTION	
	Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*		Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*
23A	1823	CC	1089	CS	26B	2394	CC	2028	CS
	1789	CC	1084	CS		2444	CS	2008	CS
2@1.0"	1843	CC	1100	CS	2@1.0"	2444	CS	2028	CS
	1818		1091			2427		2021	
1A	1891	CS	1109	CS	2B	2880	CC	2277	CS
	1866	CS	1177	CS		3010	CC	2283	CS
1@2.0"	1958	CS	1148	CS	1@2.0"	2960	CC	2284	CS
	1905		1145			2950		2281	
21A	999	CC	508	CS	24B	1364	CC	1127	CS
	995	CC	499	CS		1376	CC	1157	CS
2@0.5"	992	CC	507	CS	2@0.5"	1404	CC	1115	CS
	972		505			1381		1133	

*CS - Core Shear
CC - Core Compression Under Load Pad

TABLE 6

BEAM FLEXURE FAILURE LOADS - WRII CORE ONLY

Panel Series	L DIRECTION		W DIRECTION		Panel Series	L DIRECTION		W DIRECTION	
	Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*		Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*
29C	1304	CS	830	CS	32D	2524	CS	1690	CS
	1330	CS	804	CS		2485	CS	1806	CS
2@1.0"	1403	CS	804	CS	2@1.0"	2596	CS	1807	CS
	1346		813			2536		1768	
3C	1315	CS	670	CS	4D	2590	CS	1530	CS
	1250	CS	670	CS		2201	CS	1291	CS
1@2.0"	1290	CS	614	CS	1@2.0"	2476	CS	1747	CS
	1285		651			2422		1523	
27C	900	CS	487	CS	30D	1330	CS	1029	CS
	907	CS	505	CS		1402	CS	1036	CS
2@0.5"	884	CS	490	CS	2@0.5"	1385	CS	1061	CS
	897		494			1339		1042	

*CS - Core Shear

TABLE 7

BEAM FLEXURE FAILURE LOADS - HRH10 CORE ONLY

Panel Series	L DIRECTION		W DIRECTION		Panel Series	L DIRECTION		W DIRECTION	
	Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*		Load-Lbs.	Type Fail.*	Load-Lbs.	Type Fail.*
35E	1615	CS	1132	CS	38F	2713	CC	1896	CS
	1653	CS	1152	CS		2698	CC	1857	CS
2@1.0"	1638	CS	1122	CS	2@1.0"	2691	CC	1772	CS
	1635		1135			2701		1842	
5E	2068	CS	1280	CS	6F	2820	CC	1964	CS
	2074	CS	1392	CS		2950	CC	1935	CS
1@2.0"	2086	CS	1188	CS	1@2.0"	2990	CC	1837	CS
	2076		1287			2920		1912	
33E	927	CC	649	CS	36F	1596	CC	635	CS
	919	CC	634	CS		1612	CC	639	CS
	901	CC	619	CS	2@0.5"	1531	CC	658	CS
	916		634			1580		644	

*CS - Core Shear
CC - Core Compression Under Load Pad

TABLE 8 BEAM FLEXURE FAILURE LOADS AT 200°F

Panel Series	"L" Direction Load LBS.	"L" Direction Type Fail*	"W" Direction Load LBS.	"W" Direction Type Fail.*	Panel Series	"L" Direction Load LBS.	"L" Direction Type Fail*	"W" Direction Load LBS.	"W" Direction Type Fail*
1A	1745	Shr.	1078	Shr.	2B	2990	Comp.	2231	Shr.
	1597	Comp.	1028	Shr.		3030	Comp.	2220	Shr.
Alum.	1466	Comp.	1081	Shr.	Alum.	3120	Comp.	2217	Shr.
	1603		1062			3047		2223	
3C	580	Shr.	348	Shr.	4D	1474	Shr.	687	Shr.
	599	Shr.	348	Shr.		1484	Shr.	742	Shr.
WRII	584	Shr.	356	Shr.	WRII	1469	Shr.	675	Shr.
	588		351			1476		701	
5E	1684	Shr.	1066	Shr.	6F	2508	Comp.	1514	Shr.
	1726	Comp.	972	Shr.		2496	Comp.	1531	Shr.
HRH10	1799	Comp.	1056	Shr.	HRH10	2557	Comp.	1545	Shr.
	1736		1031			2520		1530	
9BD	71	SD	113	SD	15FB	320	SD	347	SD
	82	SD	174	SD		312	SD	310	SD
Alum./WRII	-	-	112	SD	HRH/Alum.	283	SD	305	SD
	77		133			305		321	
11FD	-	-	127	SD					

* Shr. - shear, Comp. - core compression under load pad,
SD - splice delamination.

TABLE 9 THERMAL CONDUCTIVITY COEFFICIENTS

Btu - in/hr. - sq. ft. - deg. F.

Series I.D.	Core Type Up	K	K For Panel Reversed
3C	WRII-3/8-2.5	0.83	same
4D	WRII-3/8-3.8	0.87	same
5E	HRH10-3/8-3.0	0.79	same
6F	HRH10-1/4-4.8	0.66	same
7AC	WRII	0.96	0.90
8AC	WRII	1.21	1.14
9BD	WRII	1.04	0.96
10BD	WRII	1.21	1.19
11FD	HRH10	0.72	0.72
12FD	HRH10	0.68	0.67
13EA	HRH10	0.90	0.86
14EA	HRH10	1.21	1.04
15FB	HRH10	0.83	0.80
16FB	HRH10	1.13	0.99
17FB	HRH10	1.18	1.14
18FB	HRH10	0.82	0.84

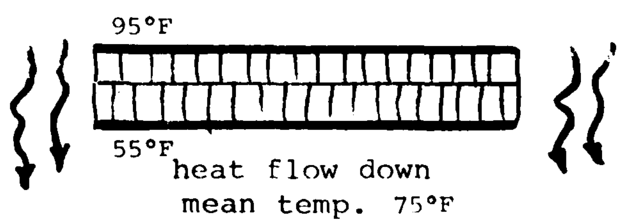


TABLE 10

STABILIZED COMPRESSIVE STRENGTH AT ROOM TEMPERATURE

Low Density						High Density					
Panel Series	Panel Type	Compressive Str. psi			Avg.	Panel Series	Panel Type	Compressive Str. psi			Avg.
1A	Alum	274	242	263	260	2B	Alum	624	591	623	613
3C	WRII	216	216	219	217	4D	WRII	584	582	557	574
5E	HRH10	350	338	327	338	6F	HRH10	693	703	699	699
7AC	Al/WRII	163	174	206	181	9BD	Al/WRII	354	357	368	360
8AC	AlWRII	174	157	166	166	10BD	Al/WRII	342	348	359	350
13EA	HRH10/Al	177	184	179	180	11FD	HRH10/WRII	387	387	401	391
14EA	HRH10/Al	195	186	189	190	12FD	HRH10/WRII	347	332	338	339
						15FB	HRH10/Al	430	404	426	420
							HRH10/Al	424	427	431	427

TABLE 11

STABILIZED COMPRESSIVE STRENGTH AT 200°F

Panel Series	Core Type	Compressive Strength psi			Avg.	Percent Strength, Retention*
1a	Alum.	195	227	223,	215	83
2B	Alum.	559	550	532,	547	89
3C	WRII	99	99	99,	99	46
4D	WRII	223	218	219,	220	38
5E	HRH10	290	306	208,	301	89
6F	HRH10	602	578	577,	586	89
9BD	Alum/WRII	195	194	179,	189	53
11FD	HRH/WRII	143	134	---,	139	36
15FB	HRH/Alum	236	240	249,	242	58

*With respect to ambient values shown in Table 10.

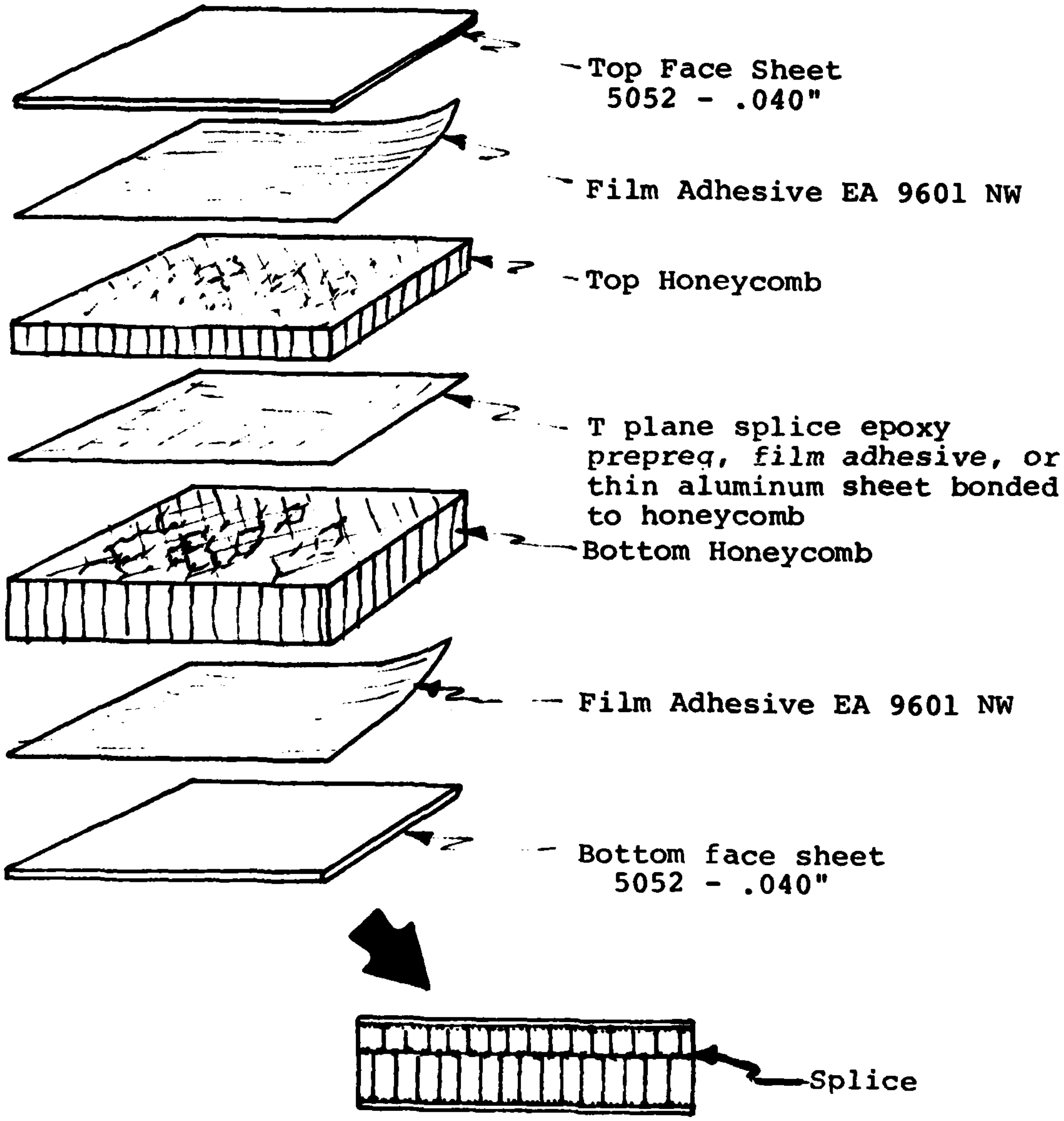


Figure 1. Construction of a Double Layer Sandwich.

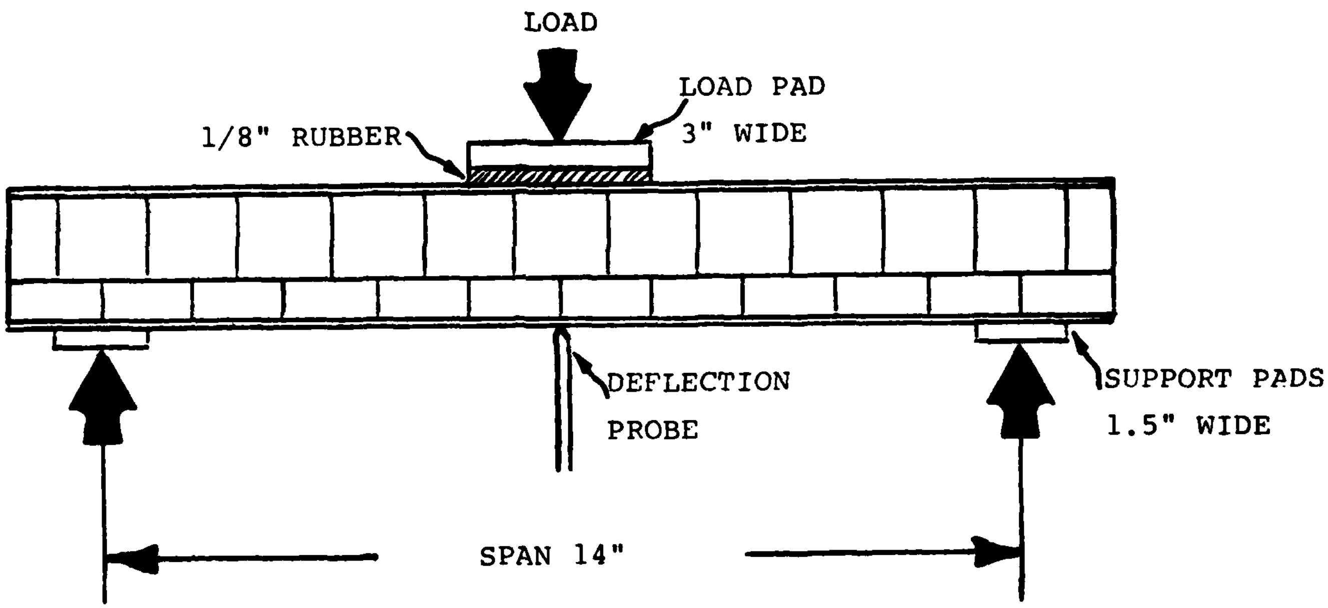


Figure 2. Beam Flexure Test Configuration.

SATEC 60,000 LB. TEST MACHINE

DYNATECH K-MATIC HEAT FLOW METER

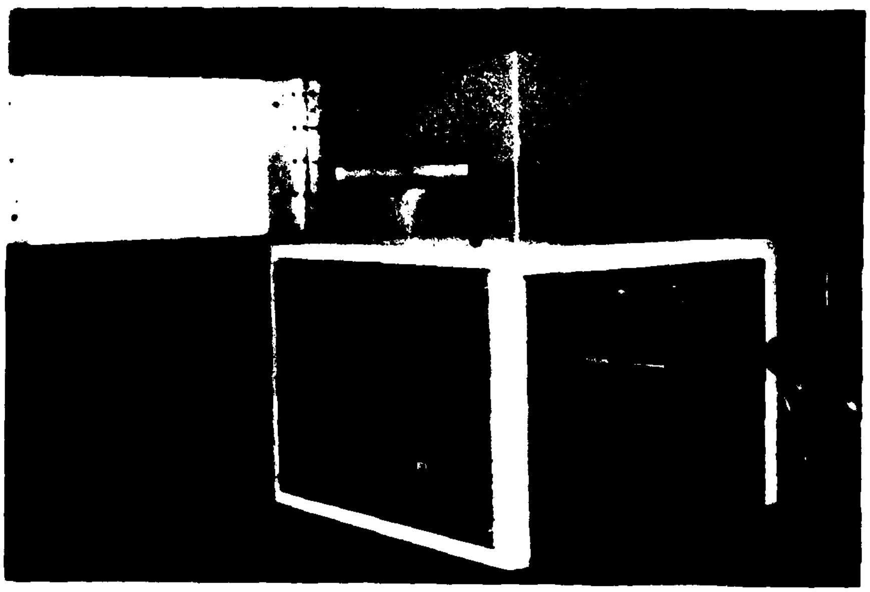
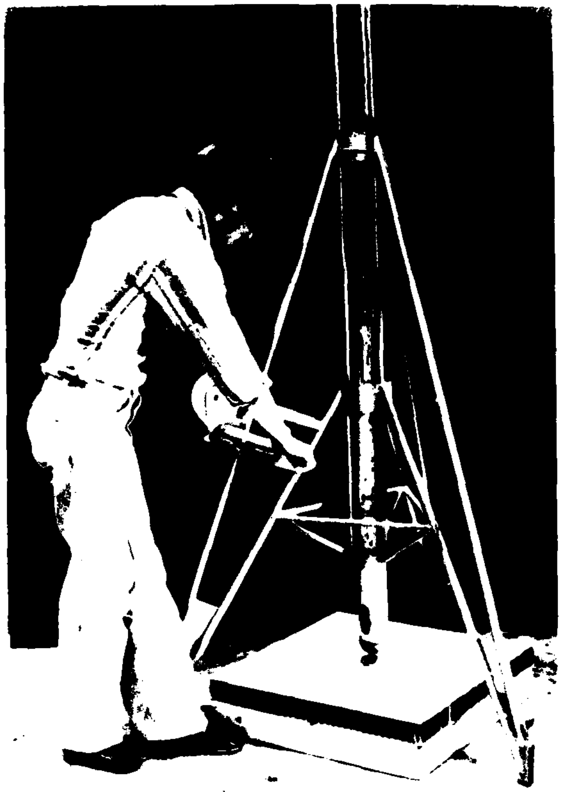


Figure 3. Hexcel R&D Test Equipment.



Drop test of a 67 lb. weight with a 3 inch diameter sperhical head at the center of a 24 x 24 inch panel.

Panels were then band sawed through Impact area to note type of damage.

Figure 4. Hexcel Trifel Tower.

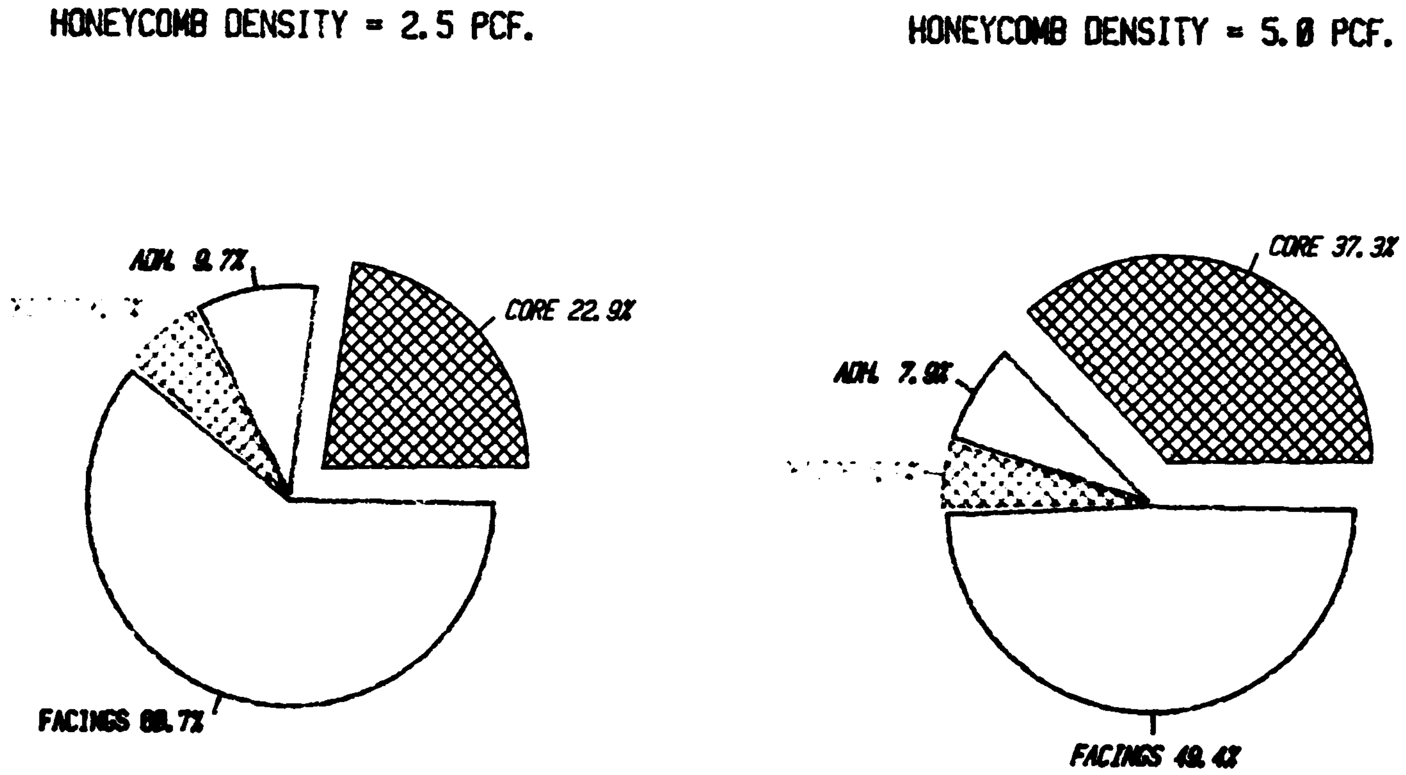
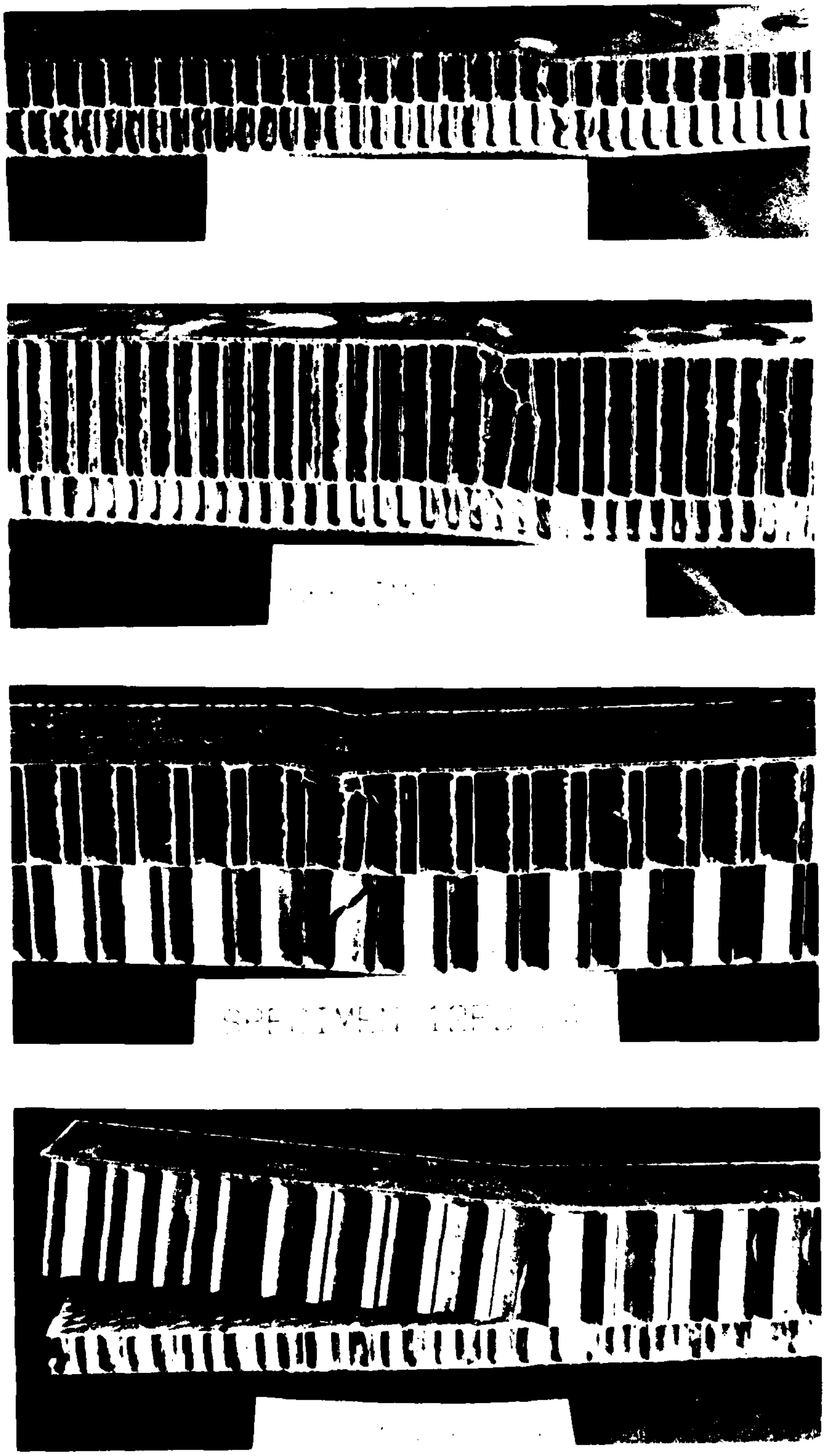


Figure 5. Panel Weight Distribution.



Good W
shear failure
1" thick panel

Good W
shear failure
2" thick panel

Shear failure
of HRH-10 and
WRII

Delamination
of the splice
between aluminum
and WRII

Figur· 6. Failures For Some Typical Beam Flexure Specimens.

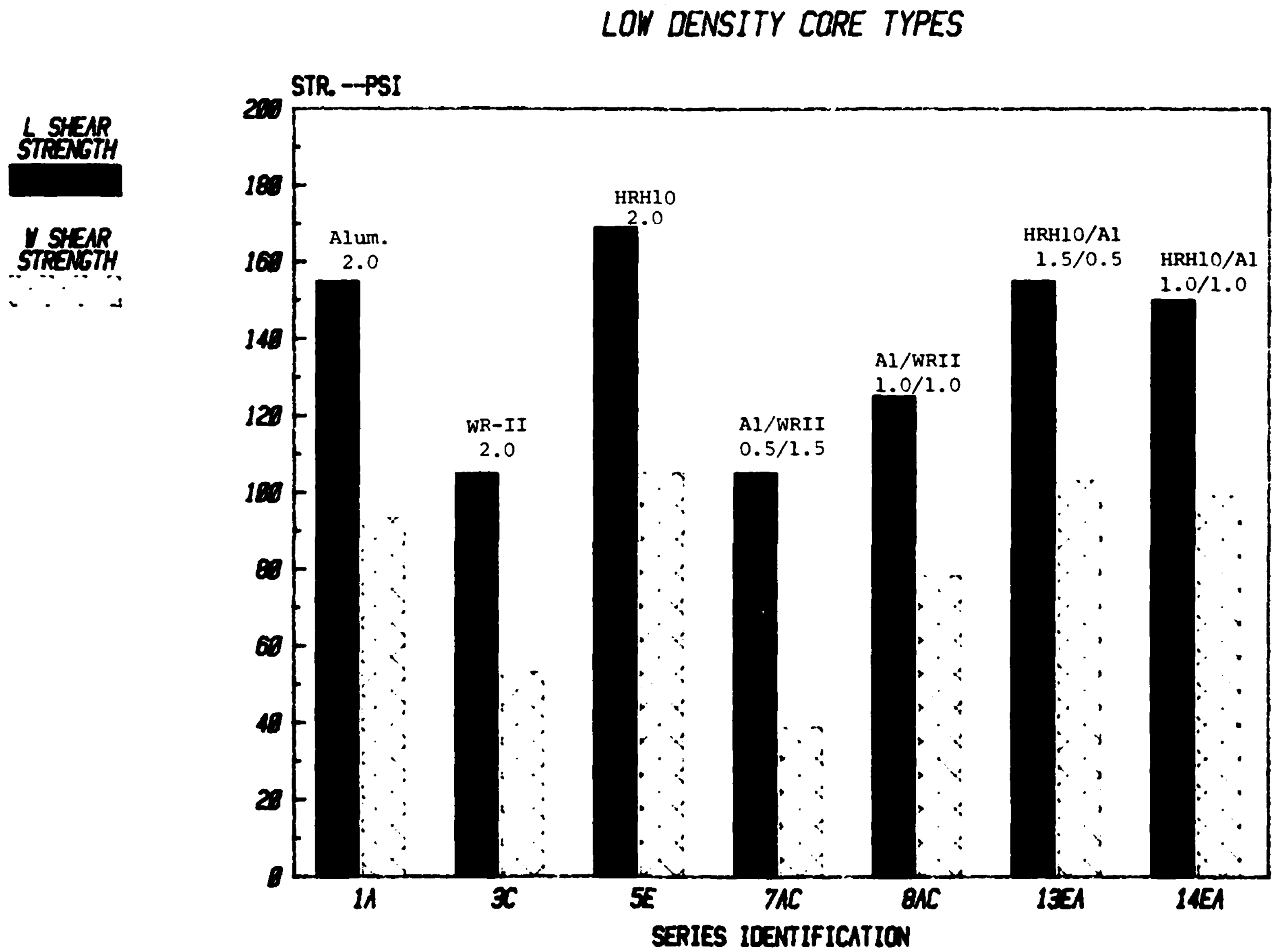


Figure 7. Flexural Shear Strength.

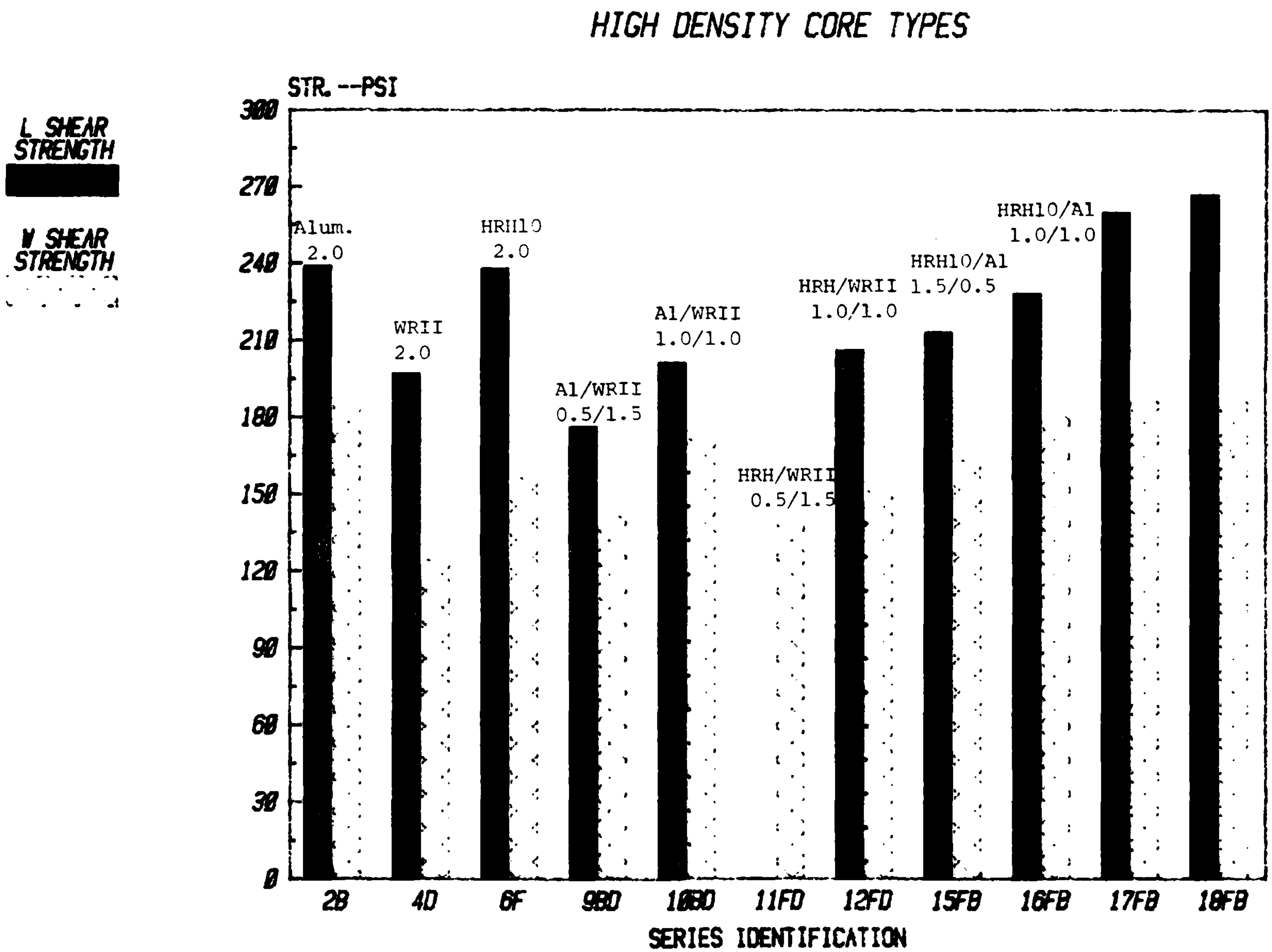


Figure 8. Flexural Shear Strength.

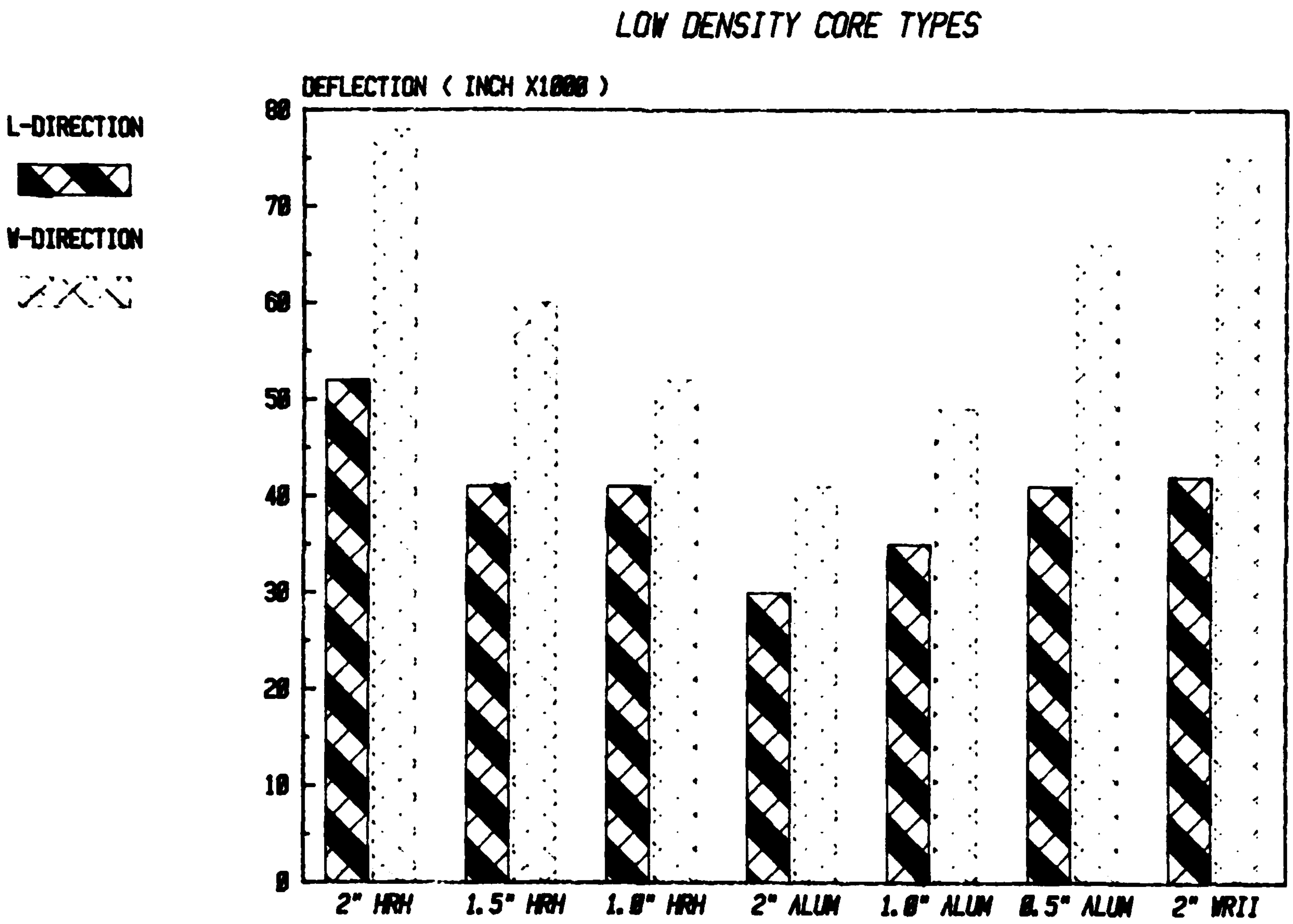


Figure 9. Beam Deflection at 500 lbs. Load.

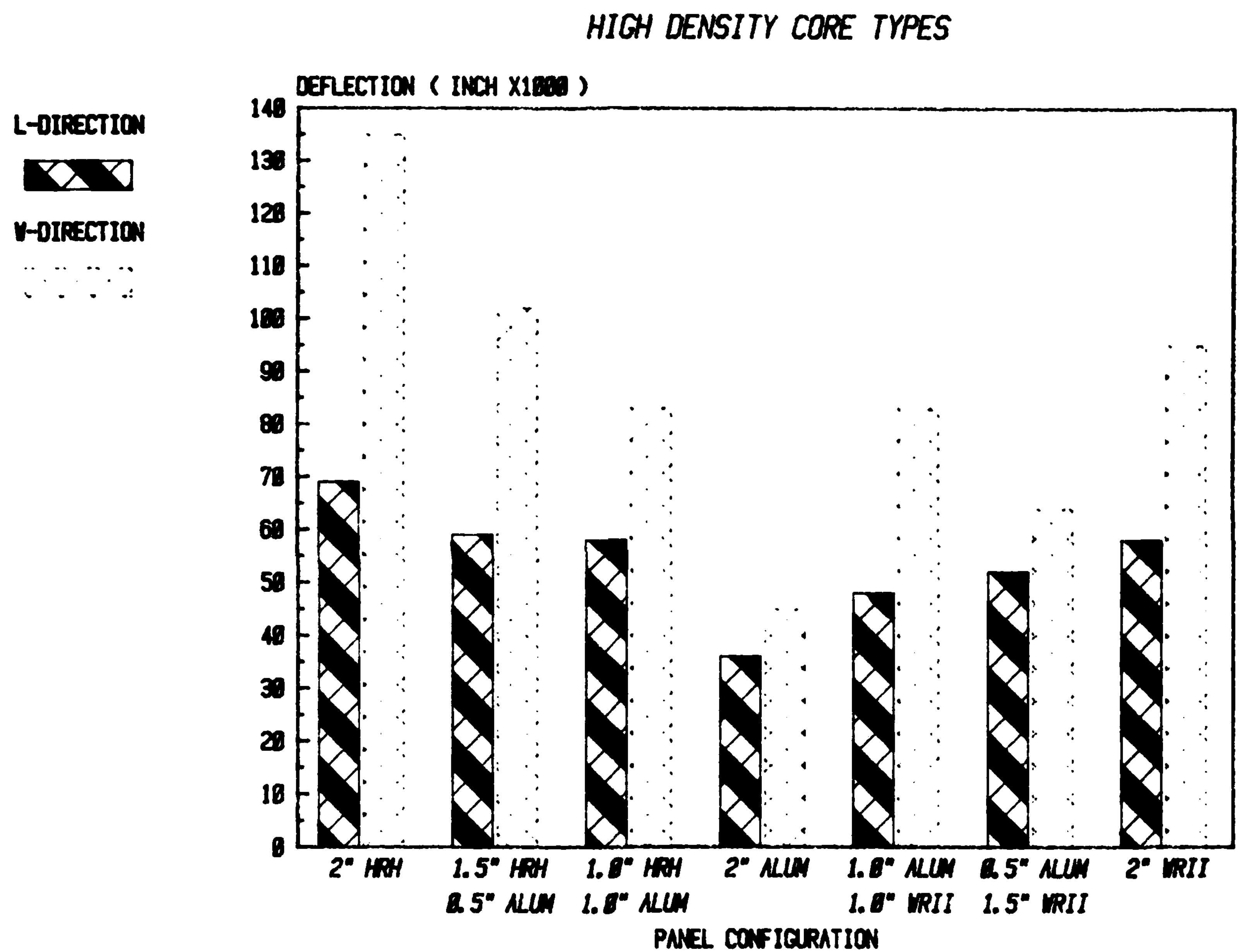


Figure 10. Beam Deflection at 1000 lbs. Load.

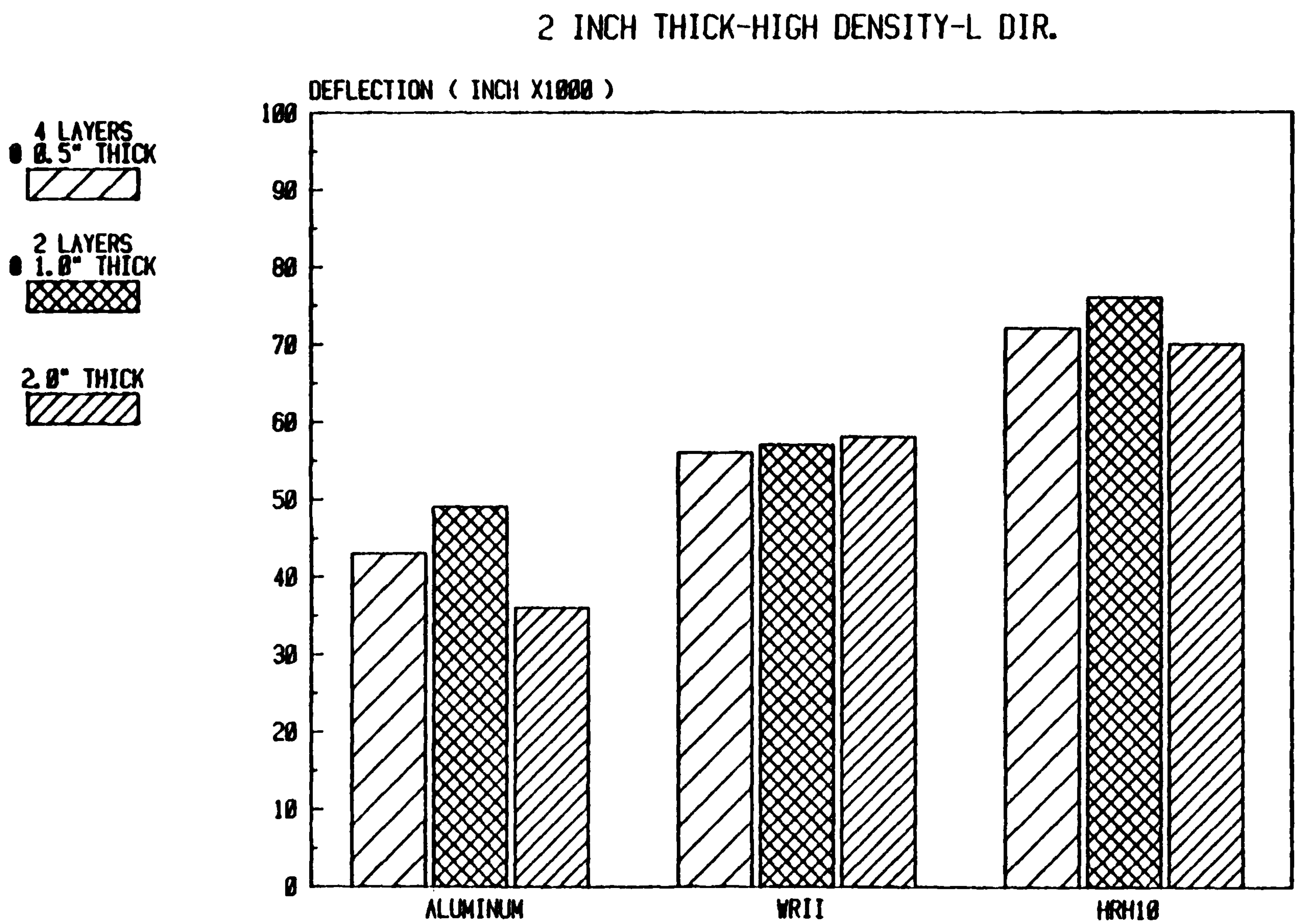


Figure 11. Beam Deflection at 1000 lbs.

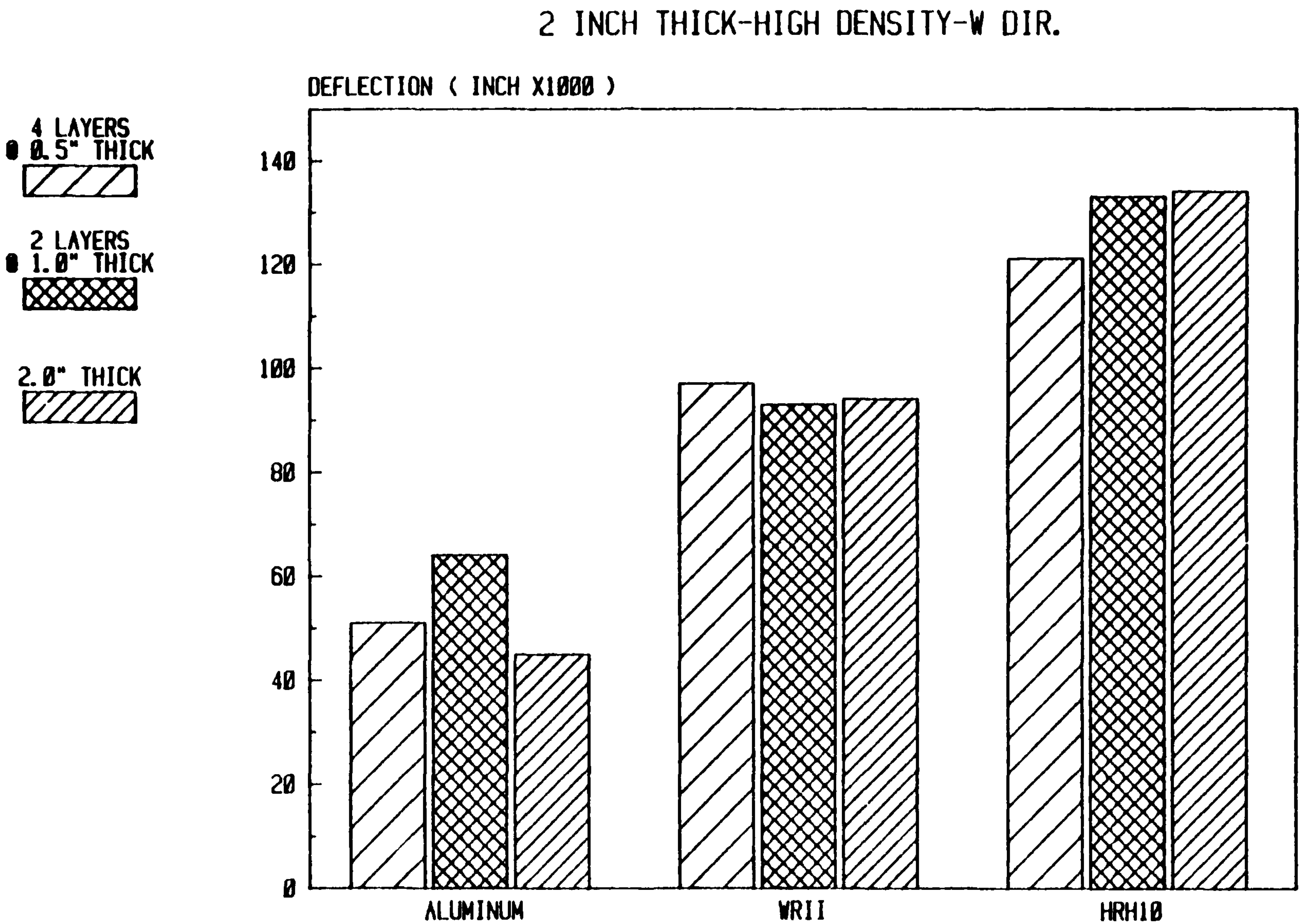


Figure 12. Beam Deflection at 1000 lbs.

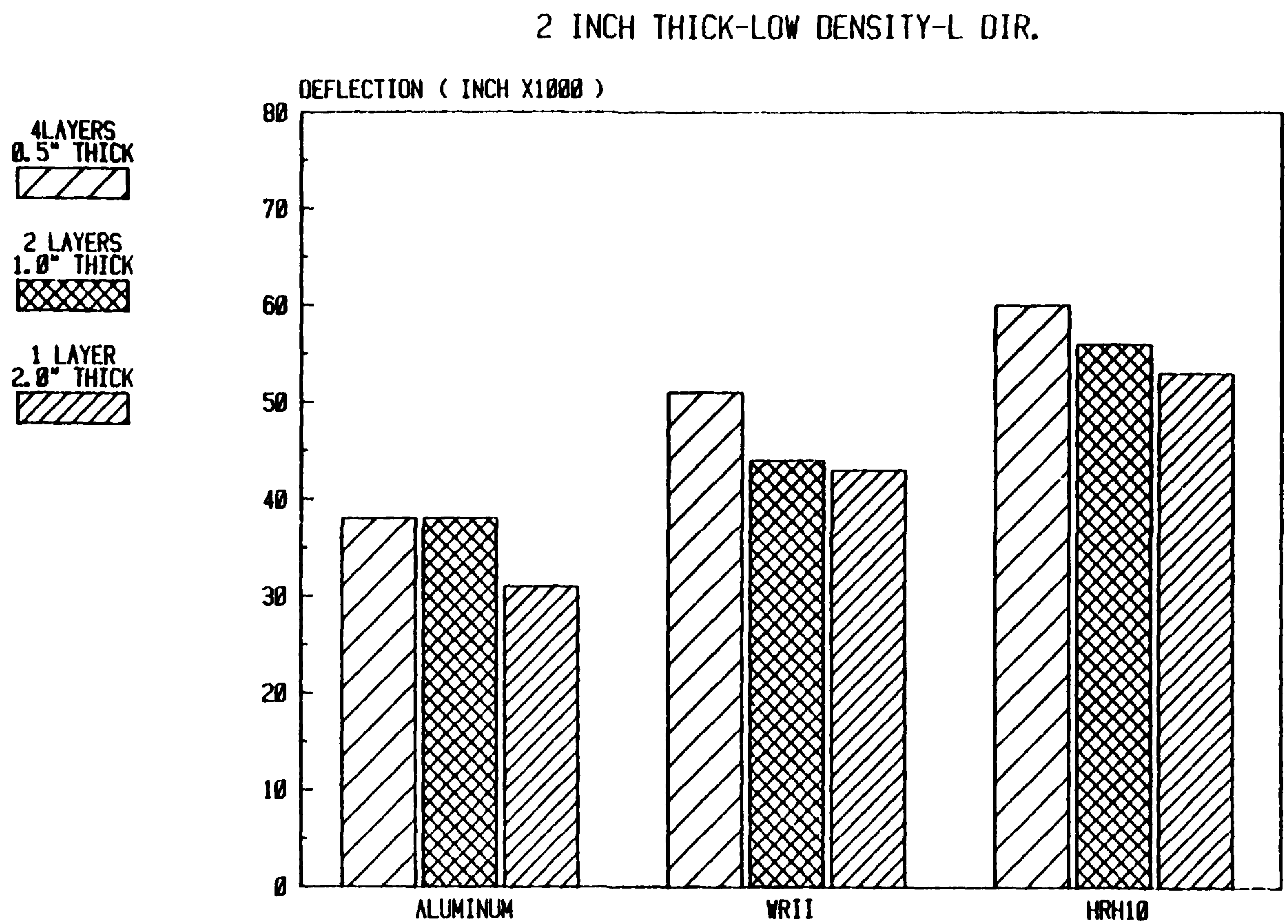


Figure 13. Beam Deflection at 500 lbs.

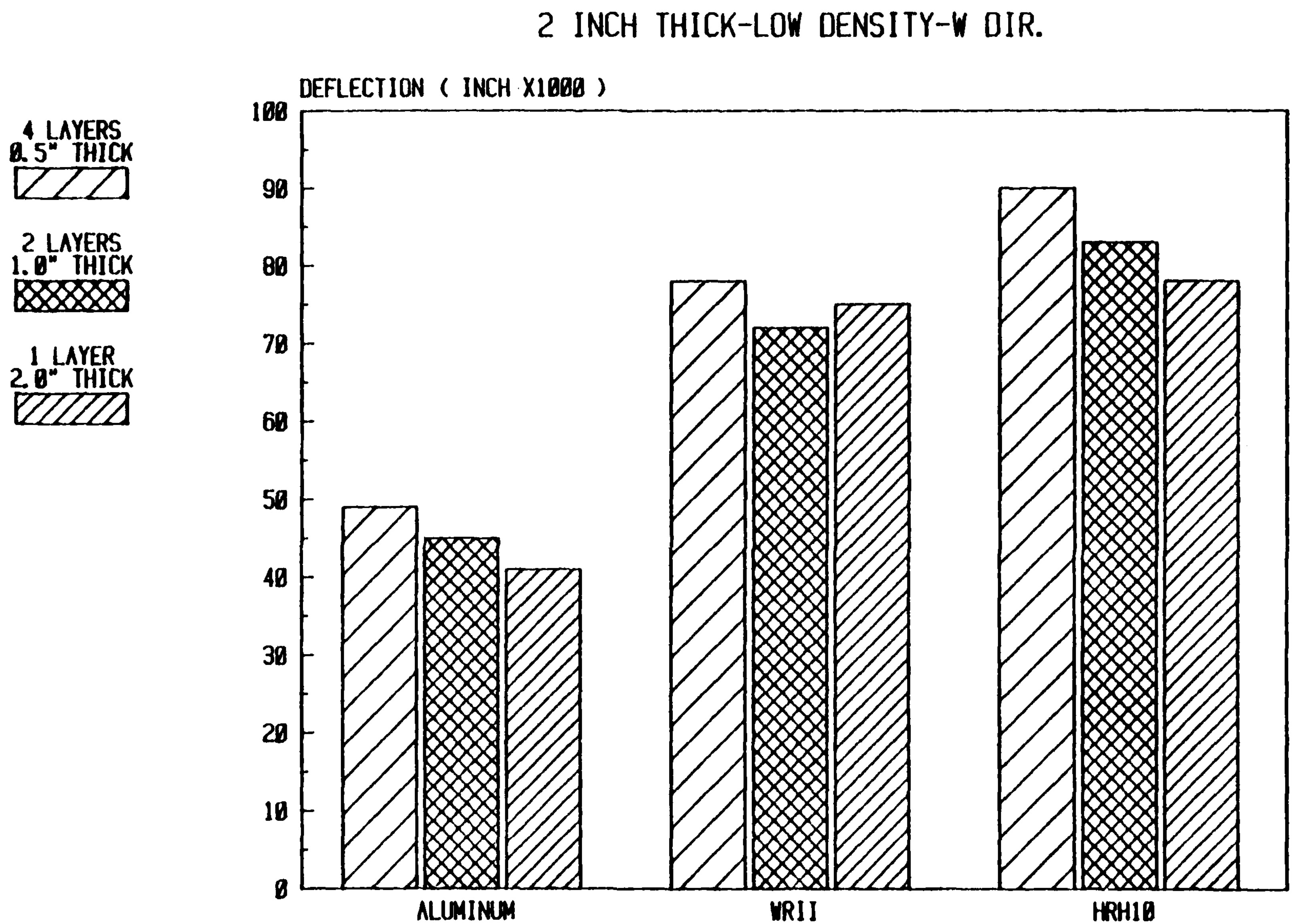


Figure 14. Beam Deflection at 500 lbs.

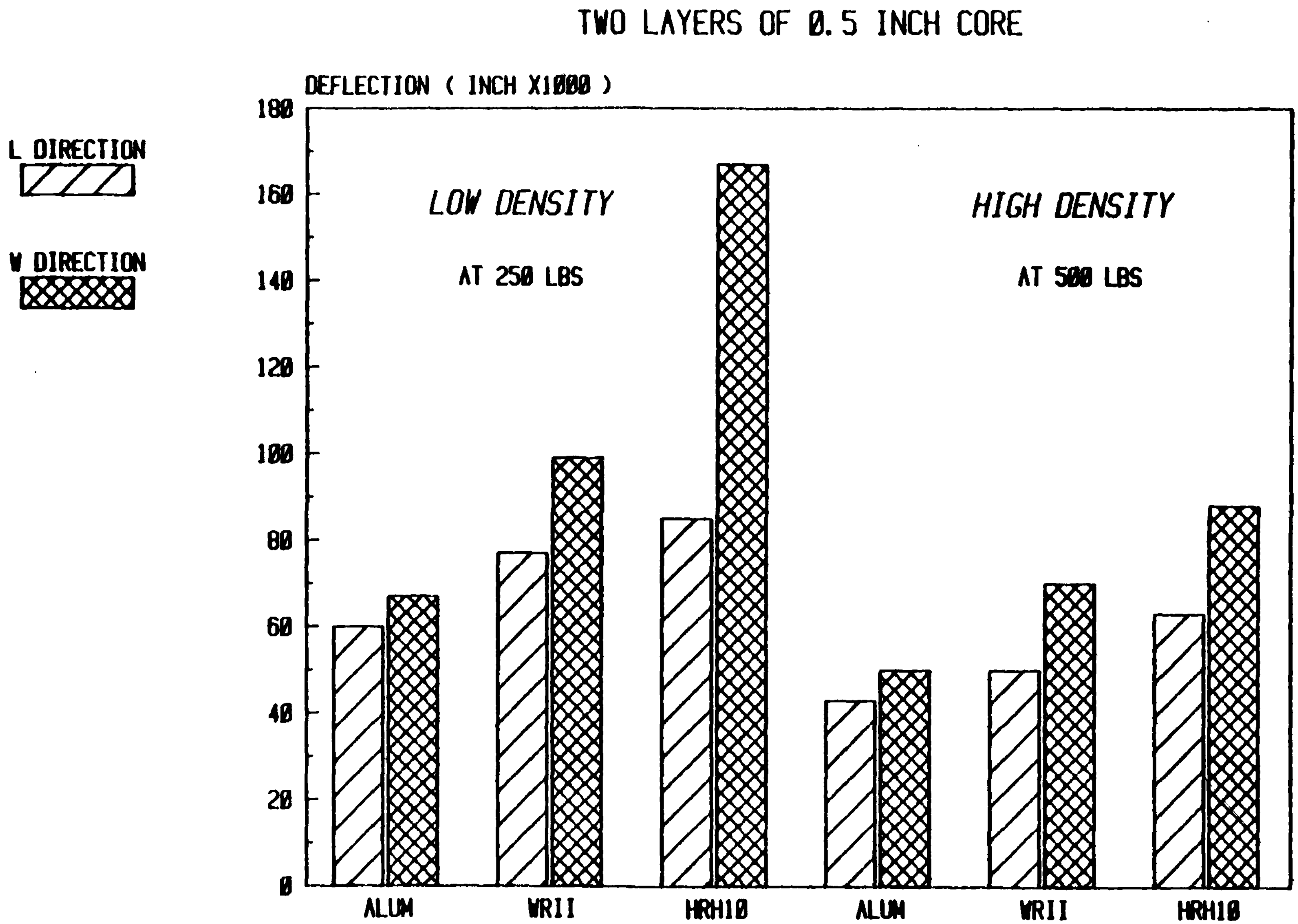


Figure 15. Beam Delfection--One Inch Panels.

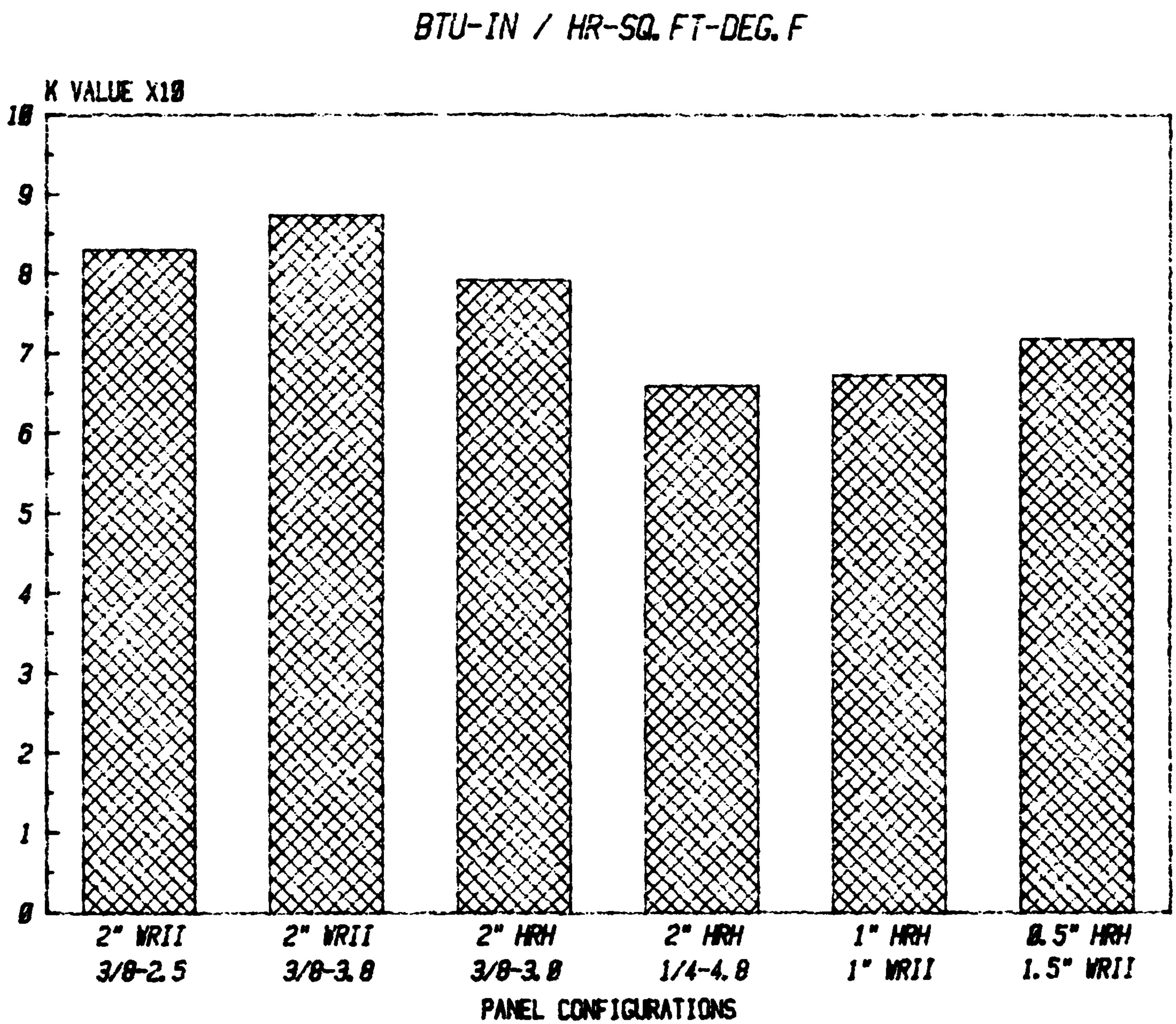


Figure 16. Thermal Conductivity Coefficient.

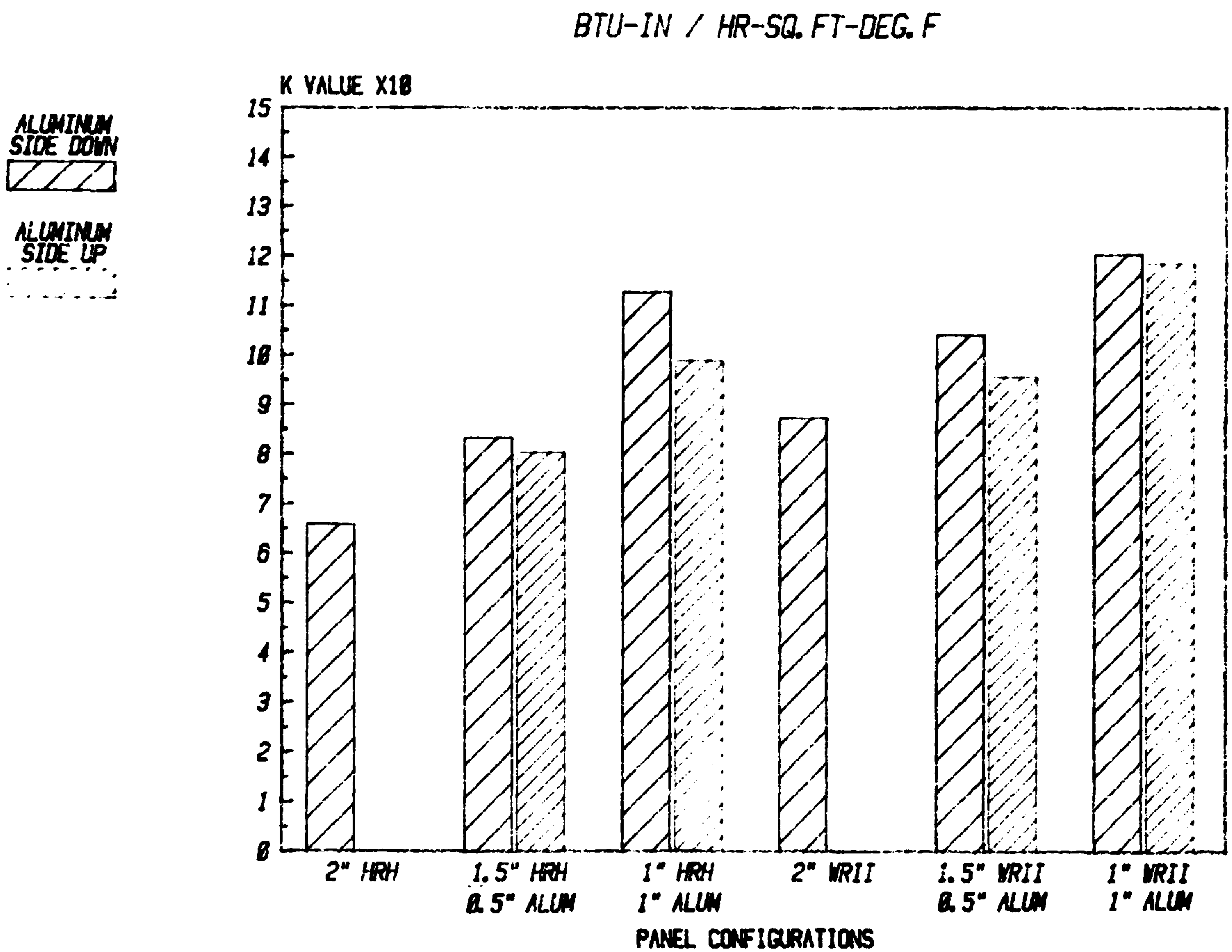


Figure 17. Thermal Conductivity Coefficient.

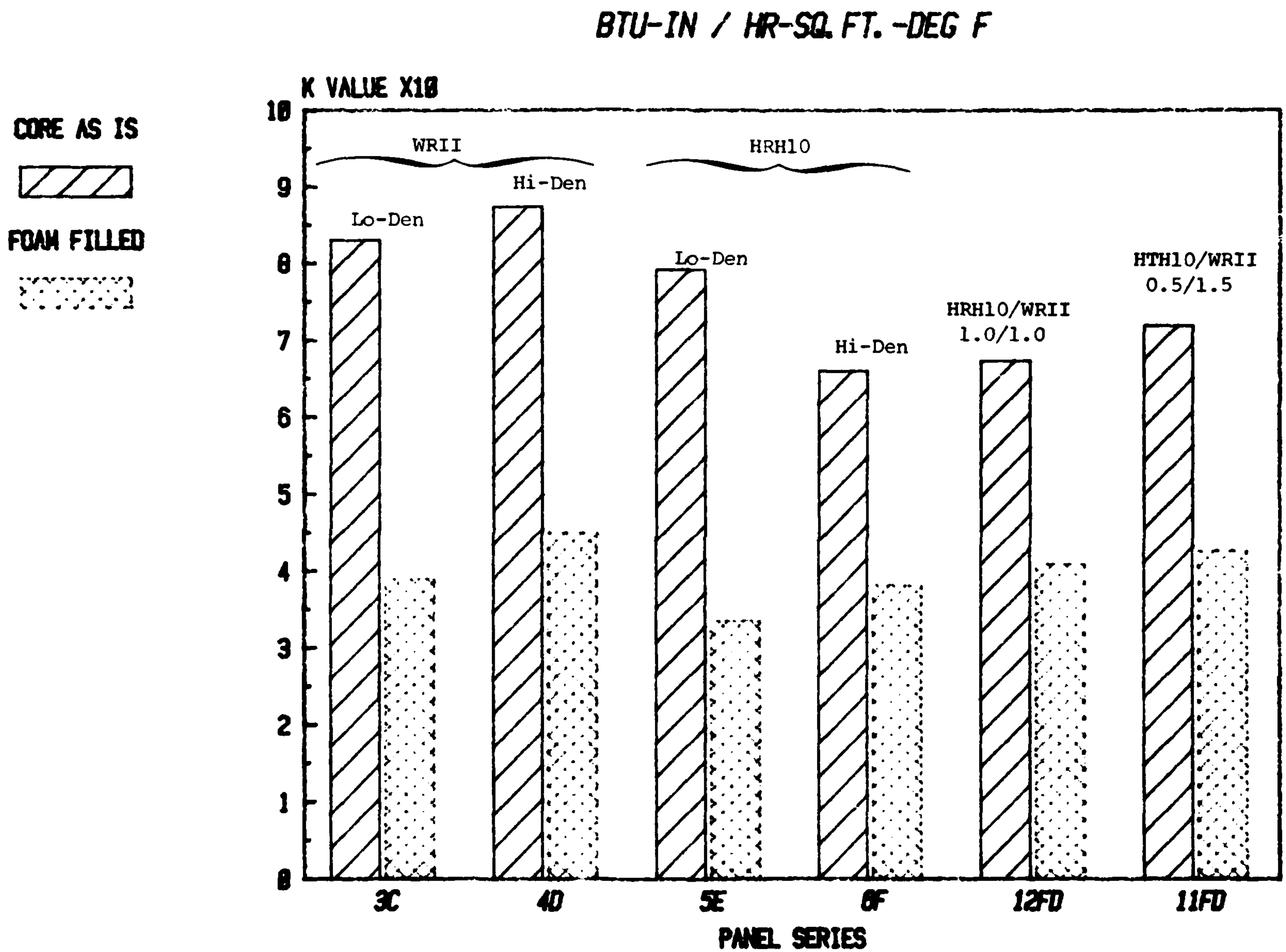


Figure 18. Thermal Conductivity Coefficient.

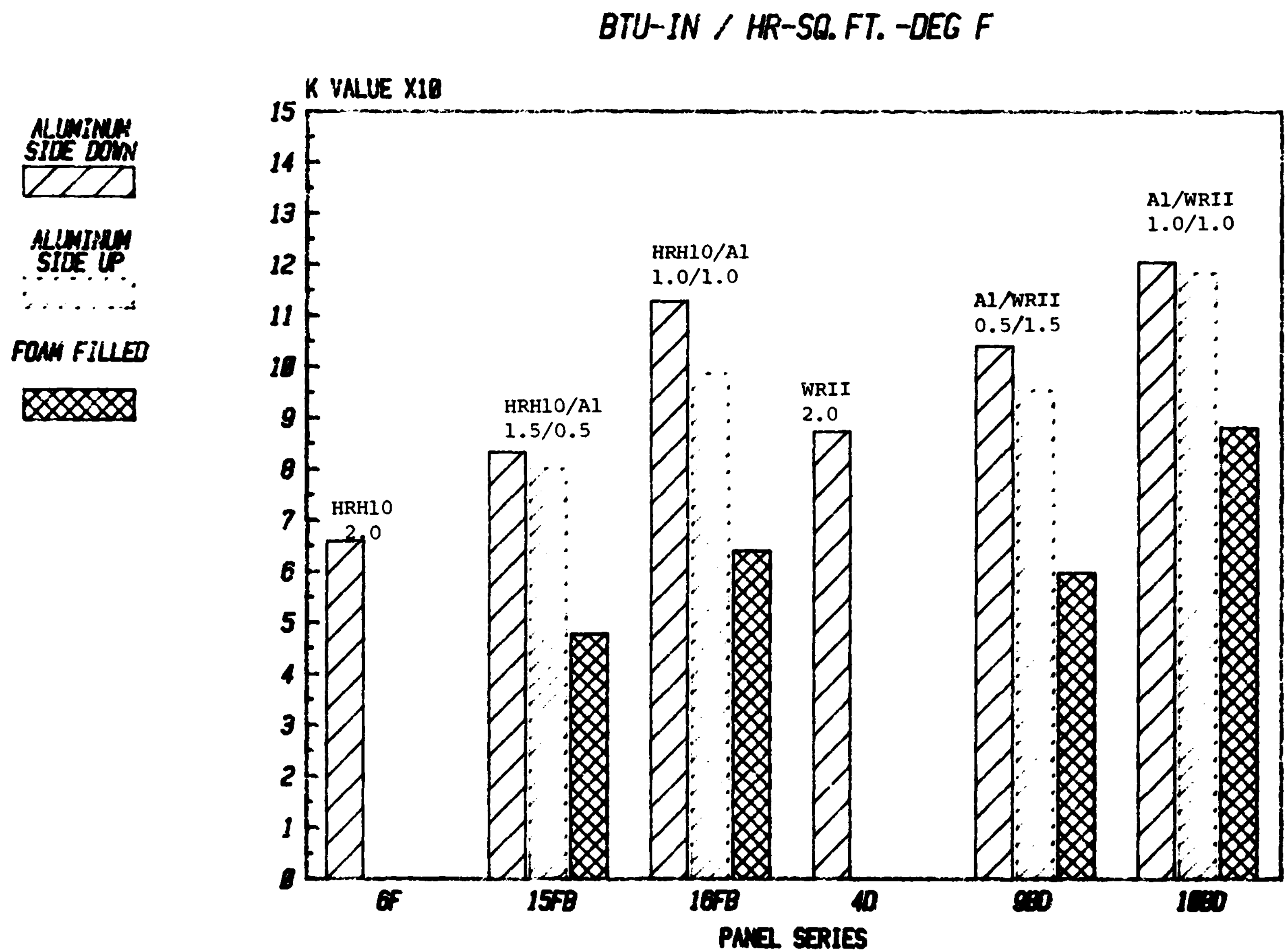
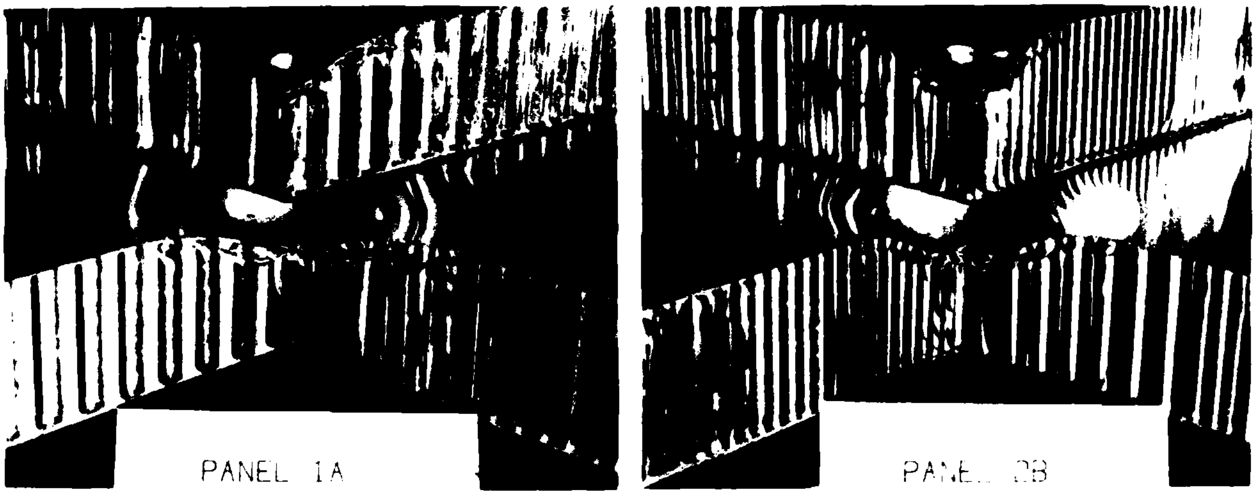
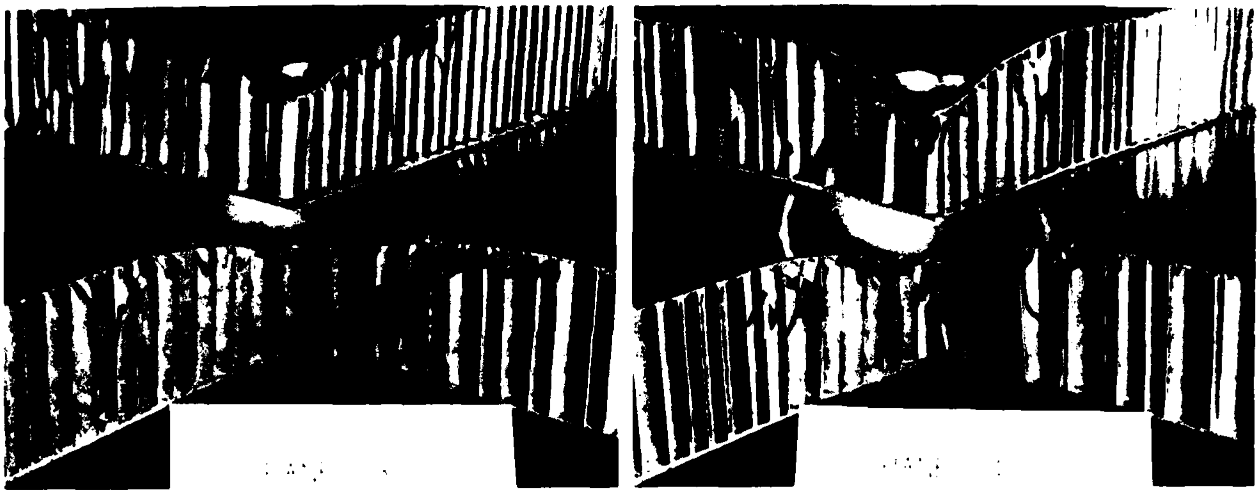


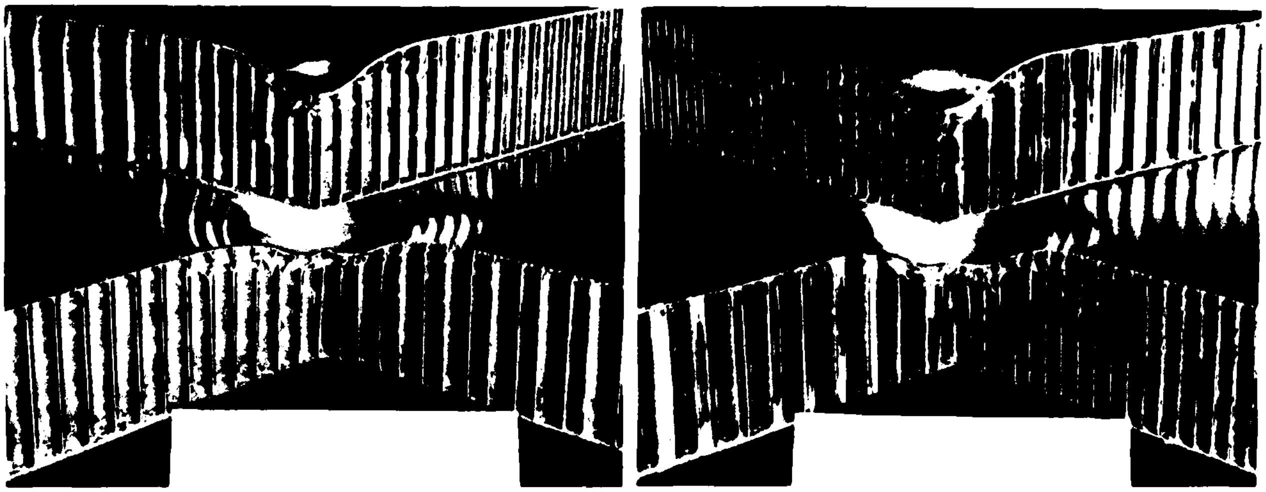
Figure 19. Thermal Conductivity Coefficient.



Aluminum Core



WRII Core



HRH-10 Core

Figure 20. Drop Test Panels Made With Full Depth Honeycomb.

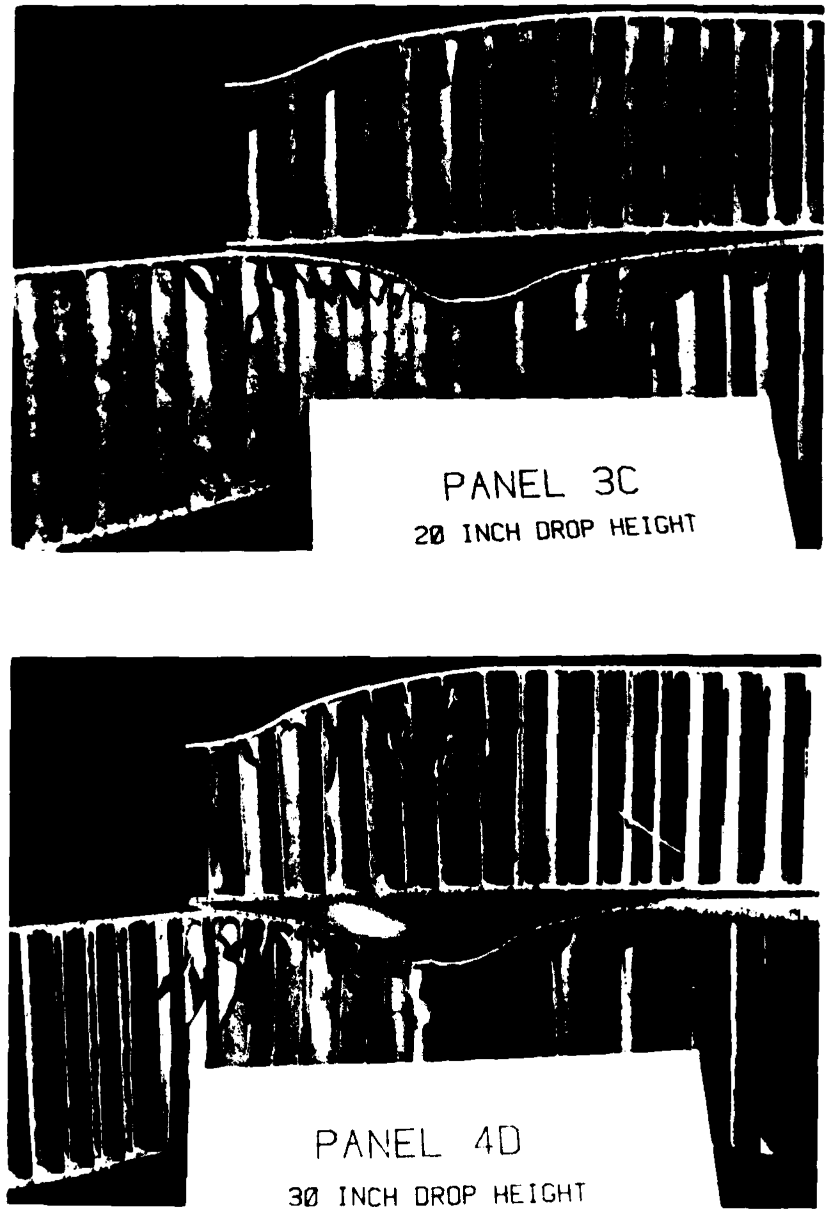
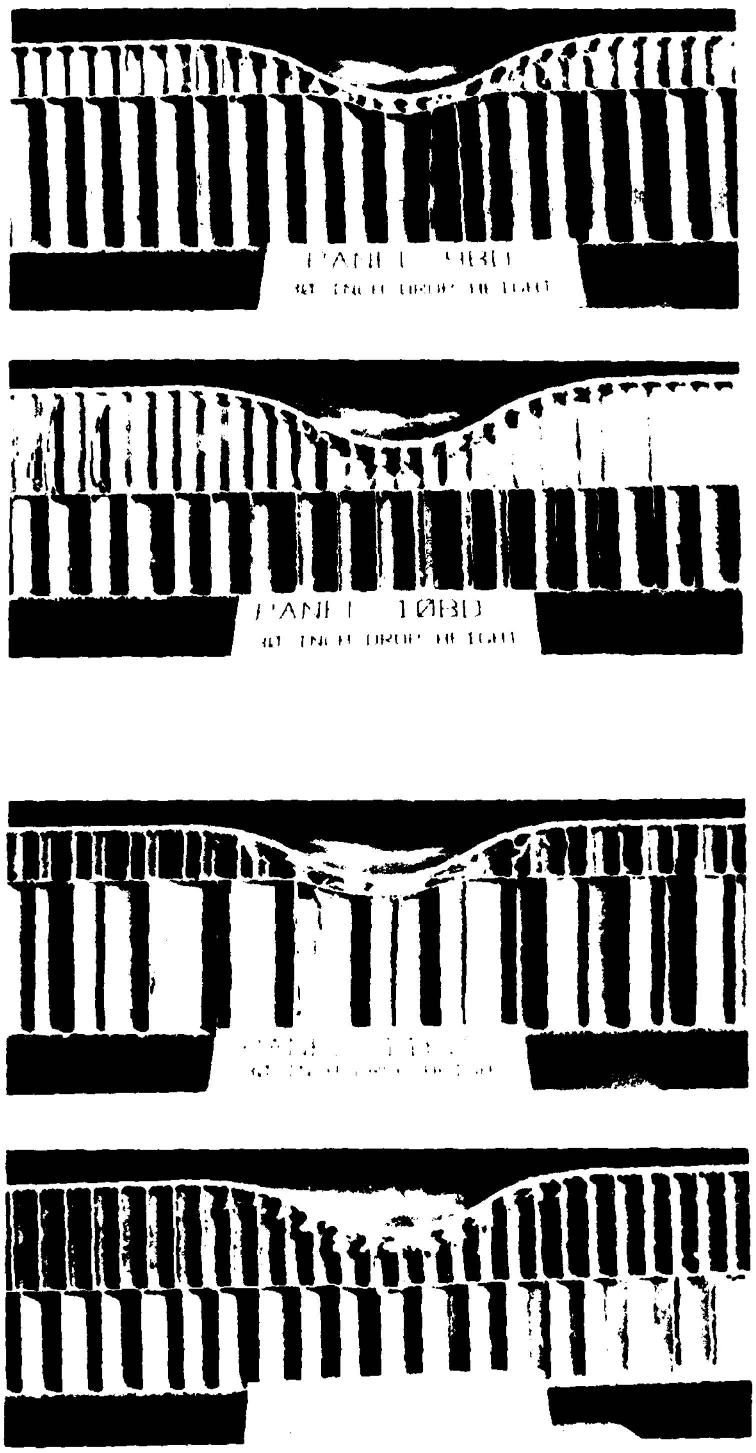


Figure 21. WRII Shows Shattered Fracture Failures After the Drop Test.



Aluminum
-
WRII

HRH-10
-
WRII

Figure 22. Close-Up Cross Sections For Various Drop Test Panels.

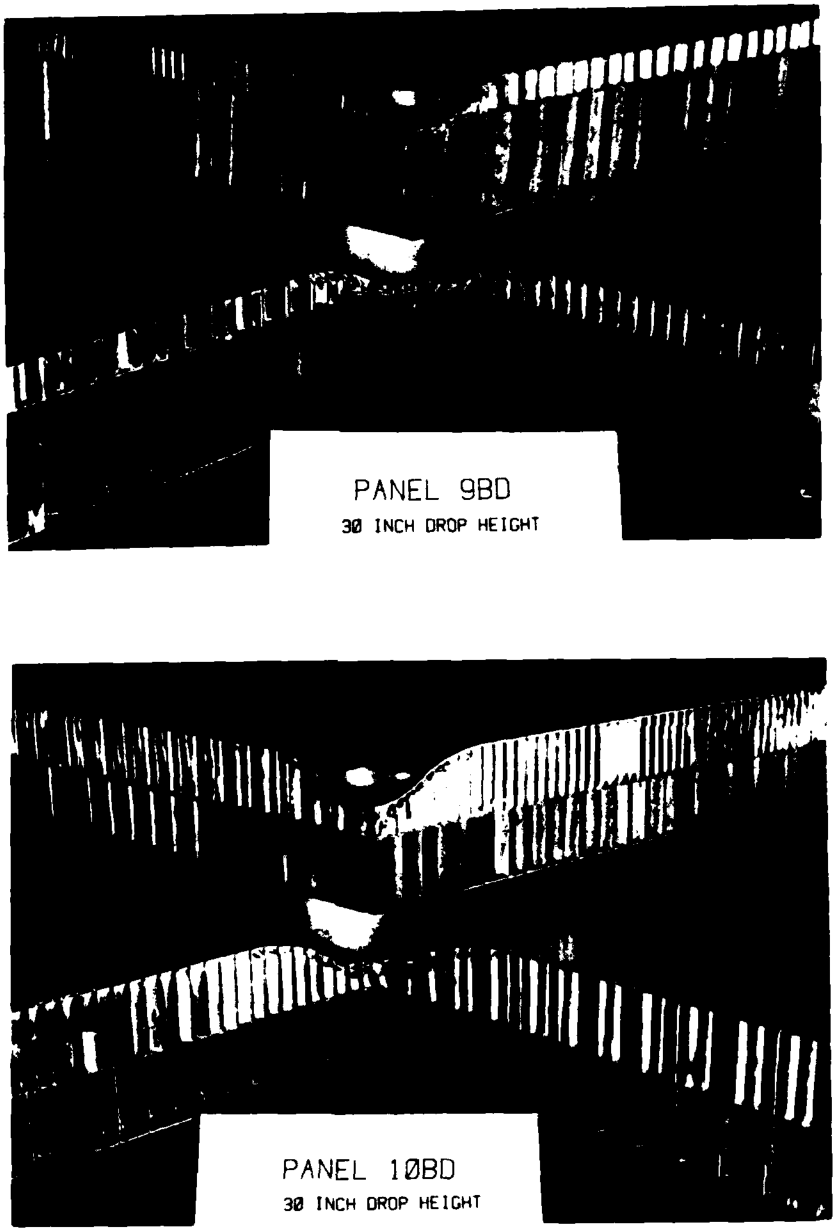


Figure 23. Drop Test Comparison Between 0.5" Aluminum/ 1.5" WRII and 1.0" Aluminum/1.0" WRII.

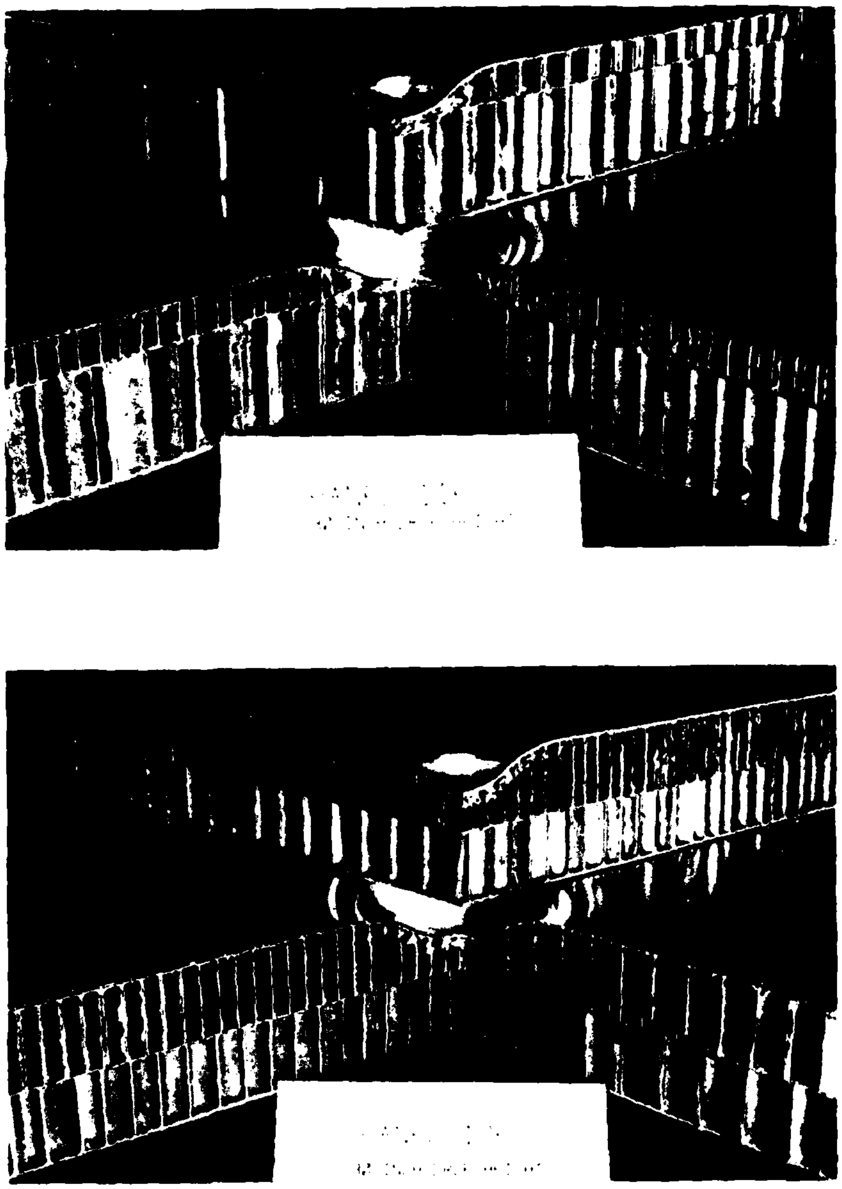
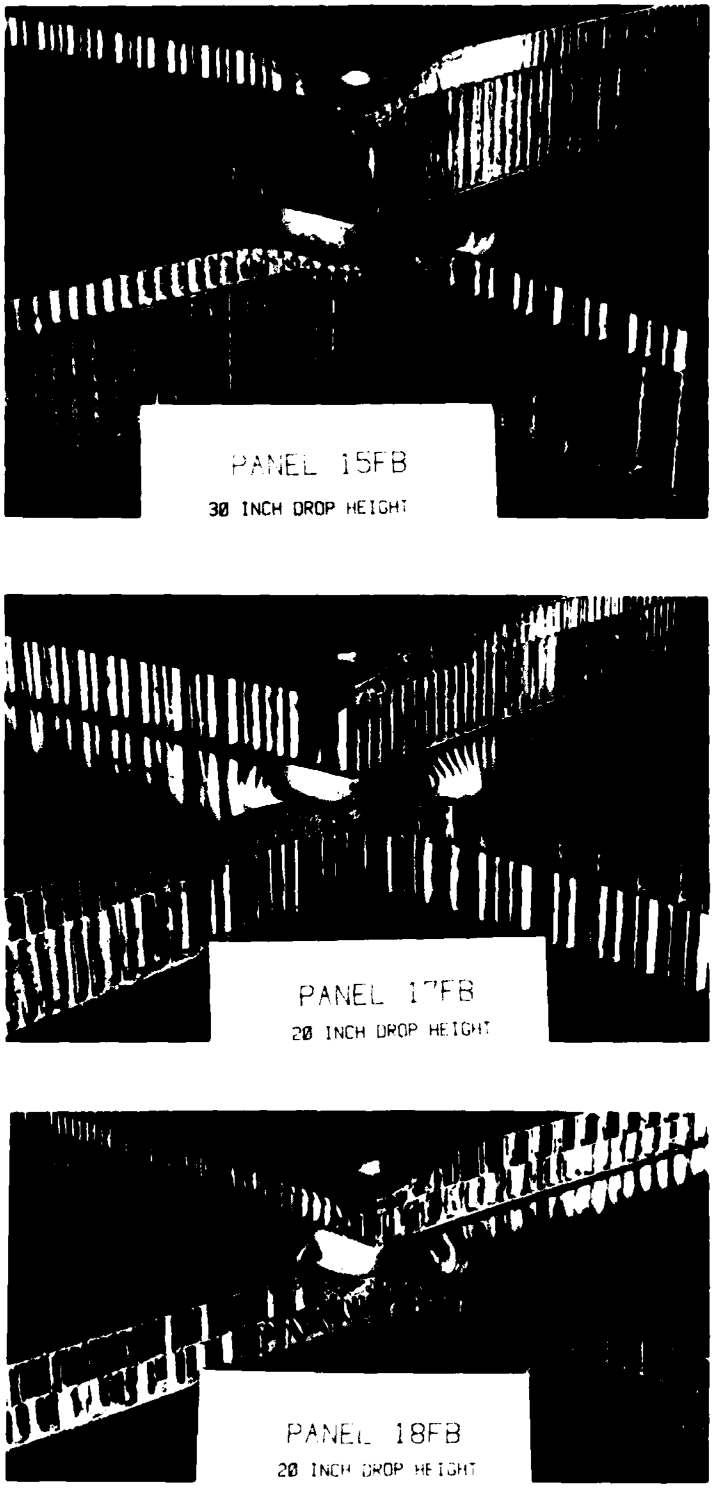


Figure 24. Drop Test Comparison Between 0.5" HRH10/ 1.5" WRII and 1.0" HRH10/1.0" WRII.



2.0" thick
Aluminum/HRH-10

1.5" thick
HRH-10/Aluminum

1" thick
HRH-10/Aluminum

Figure 25. Drop Tests on Panels of Different Thicknesses.

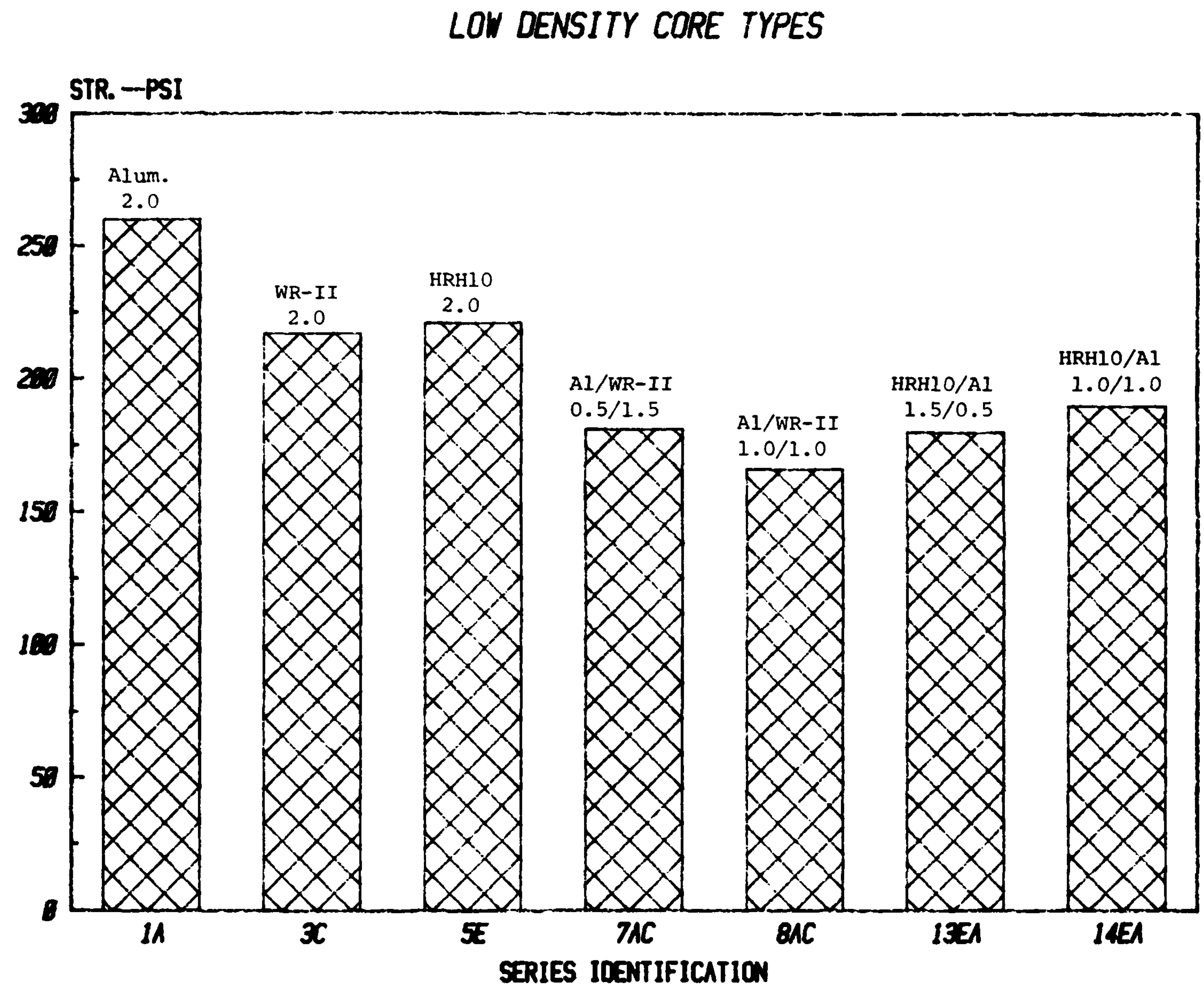


Figure 26. Room Temperature Compressive Strength.

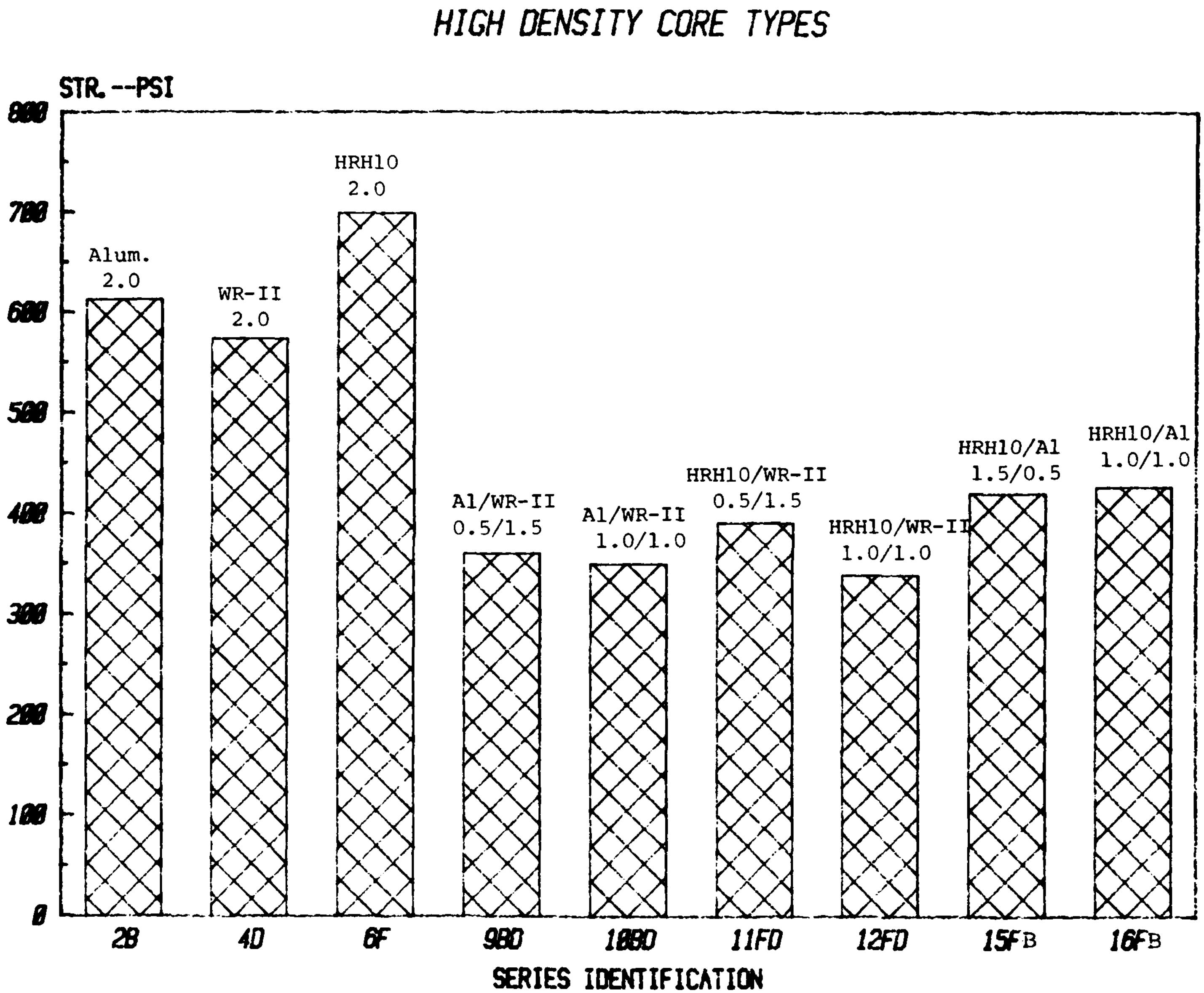


Figure 27. Room Temperature Compressive Strength.

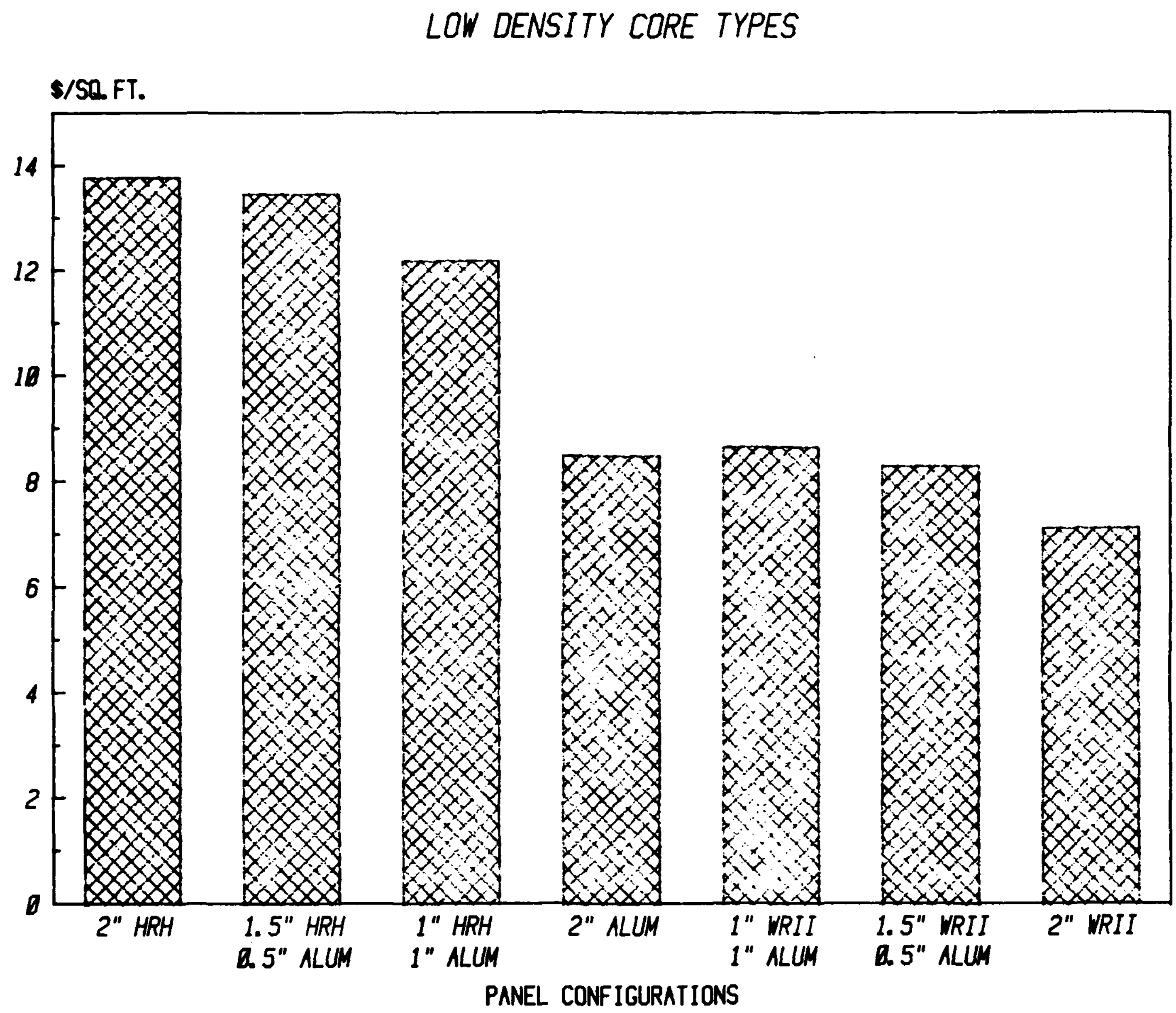


Figure 28. Estimated Panel Costs.

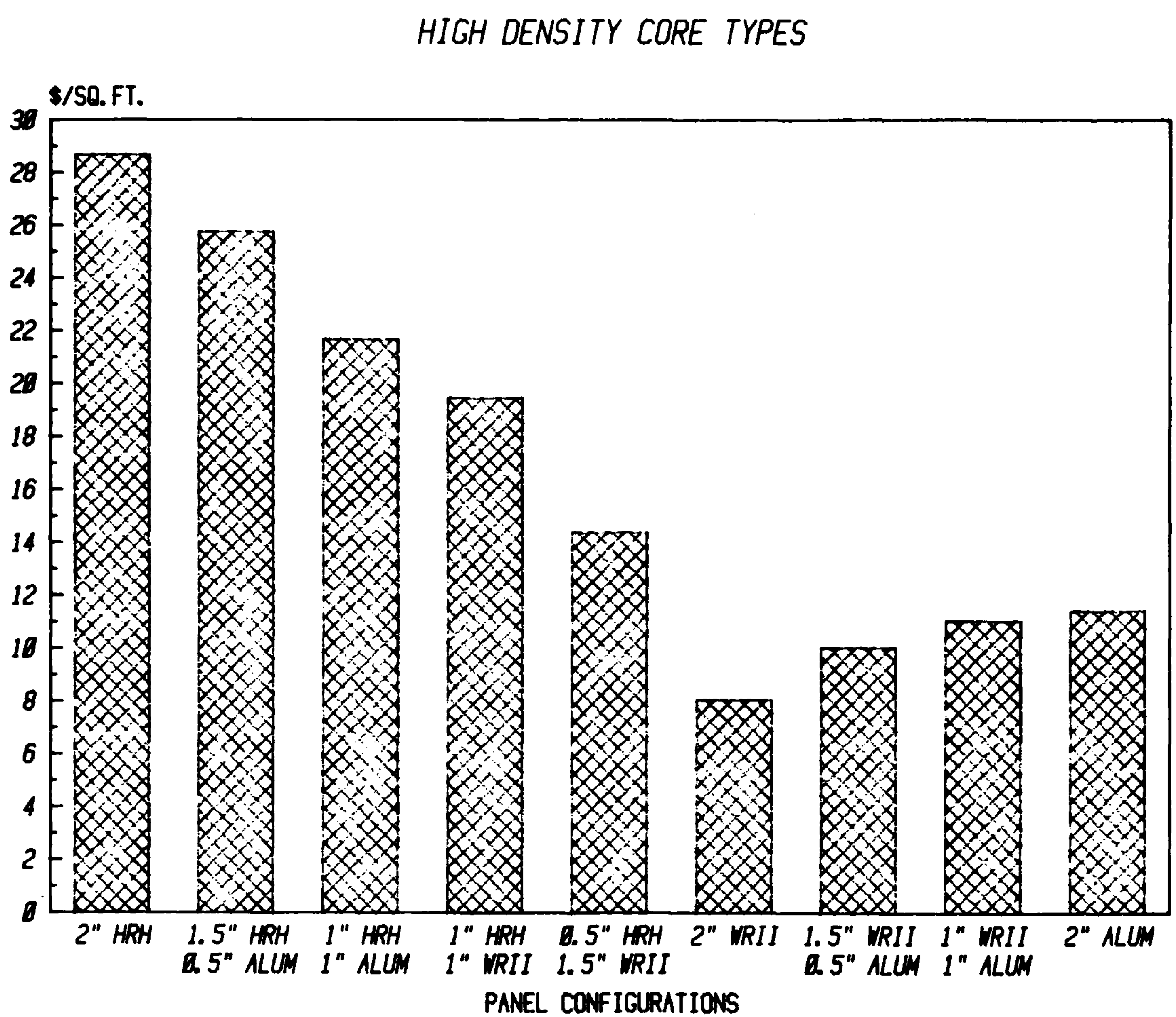


Figure 29. Estimated Panel Costs.

APPENDIX A

INDIVIDUAL LOAD - DEFLECTION CURVES

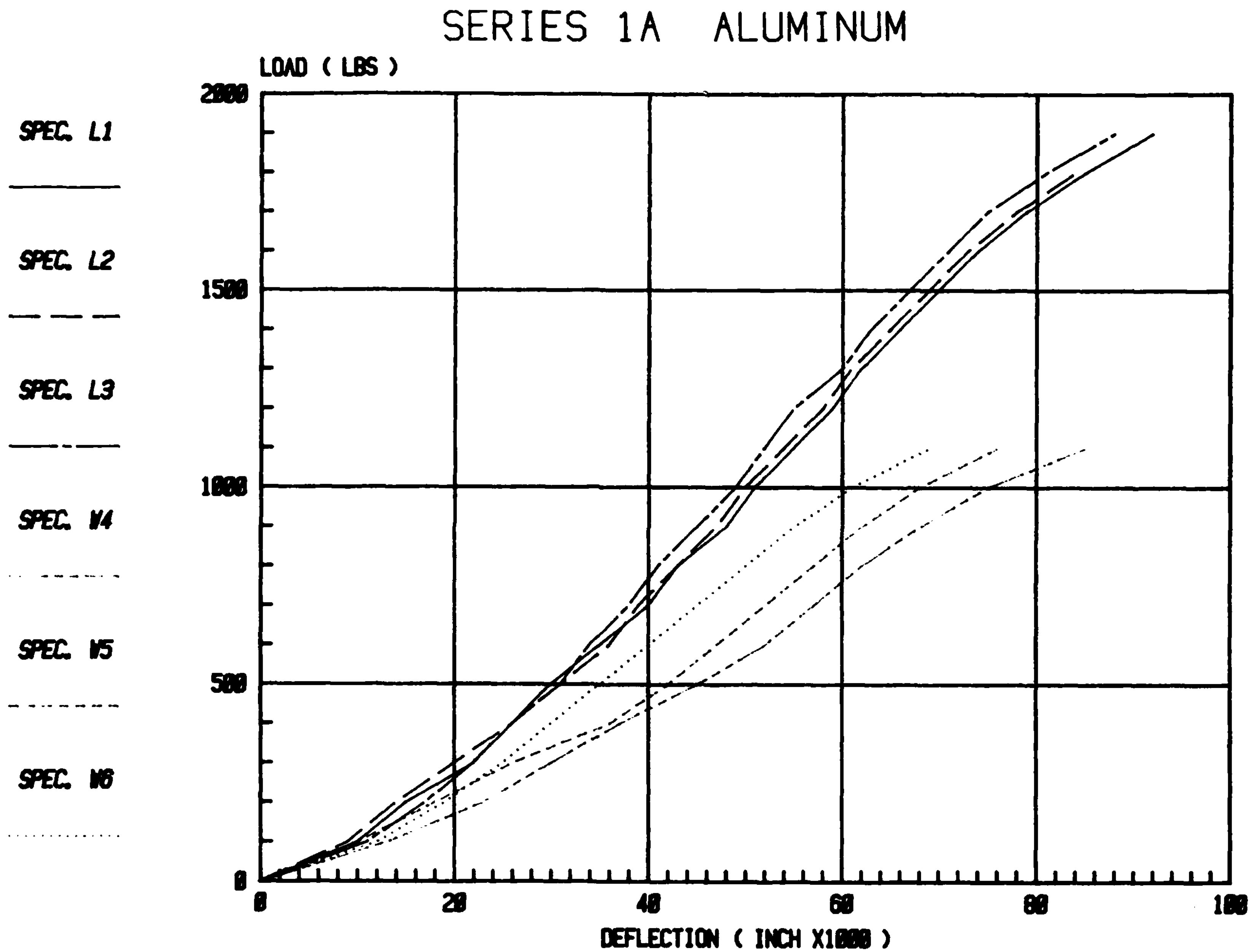
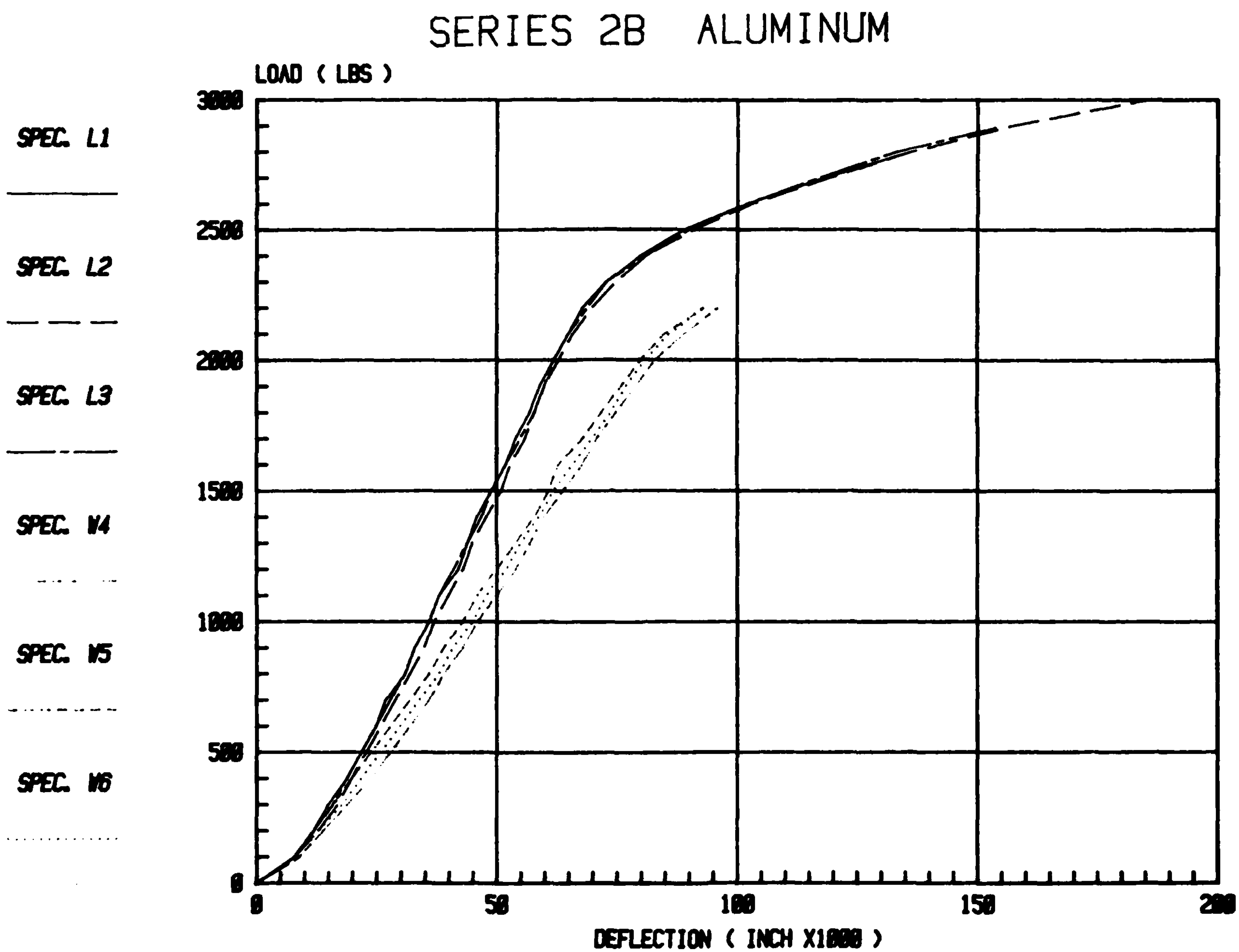


Figure A.1. Load Deflection.



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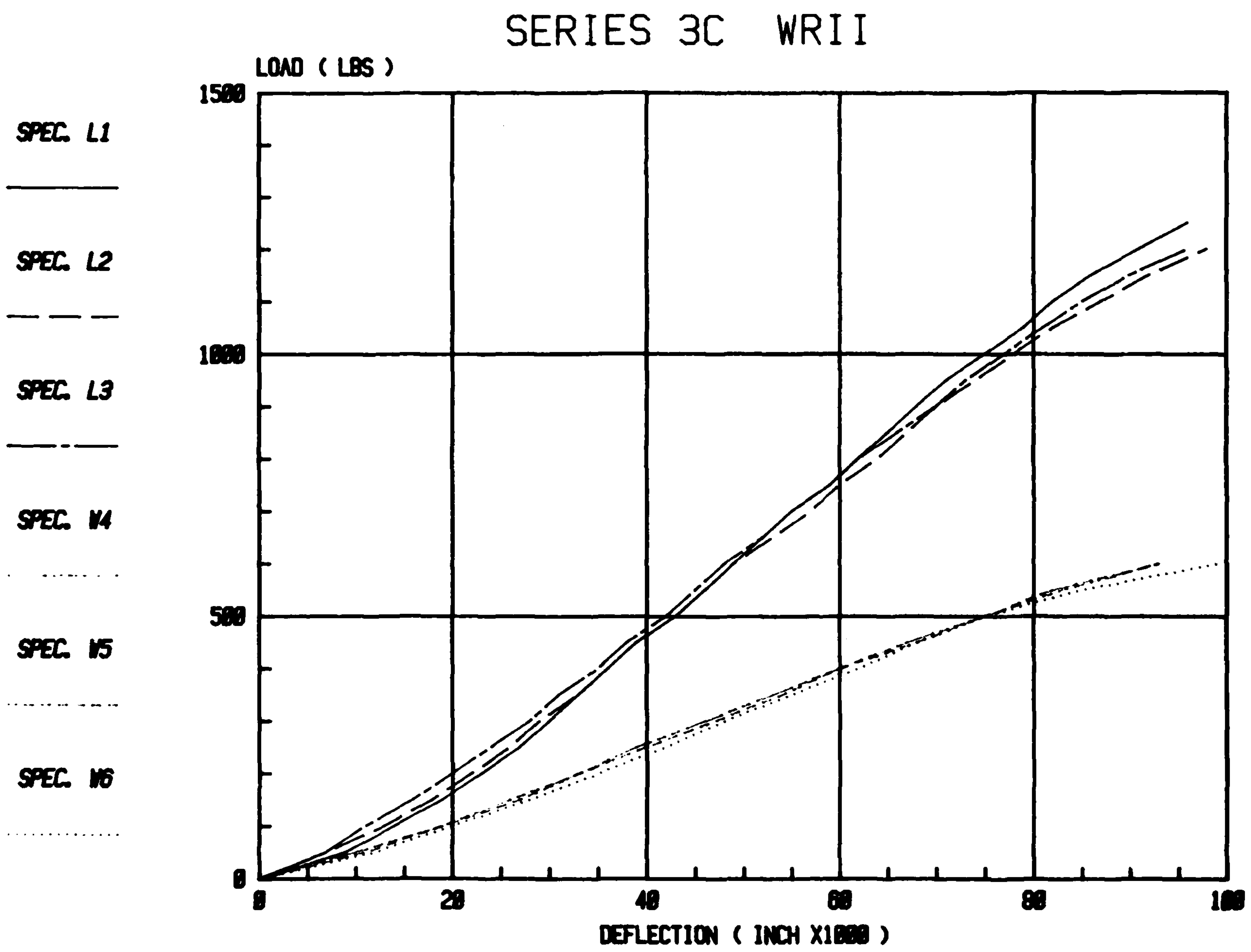


Figure A.3. Load Deflection.

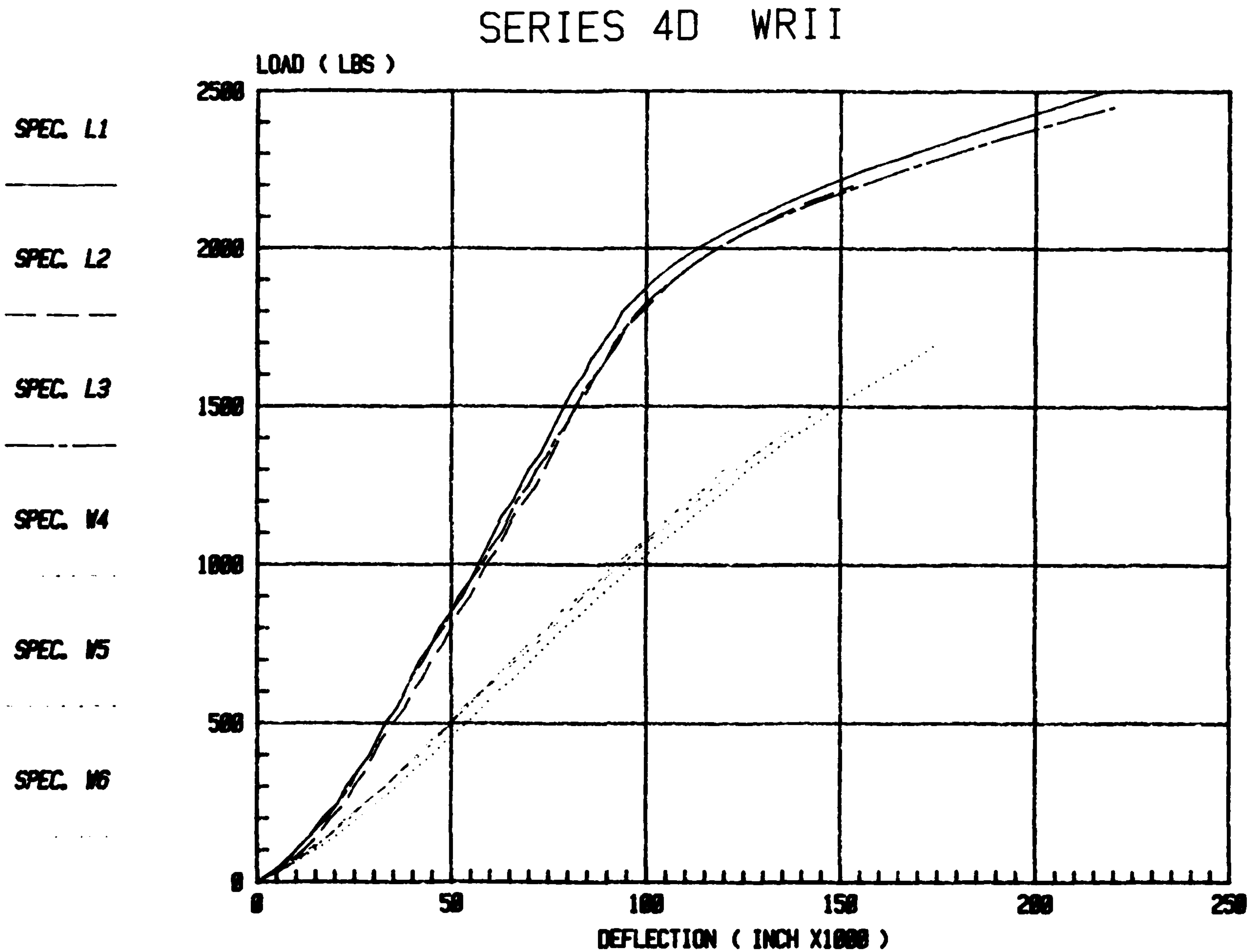
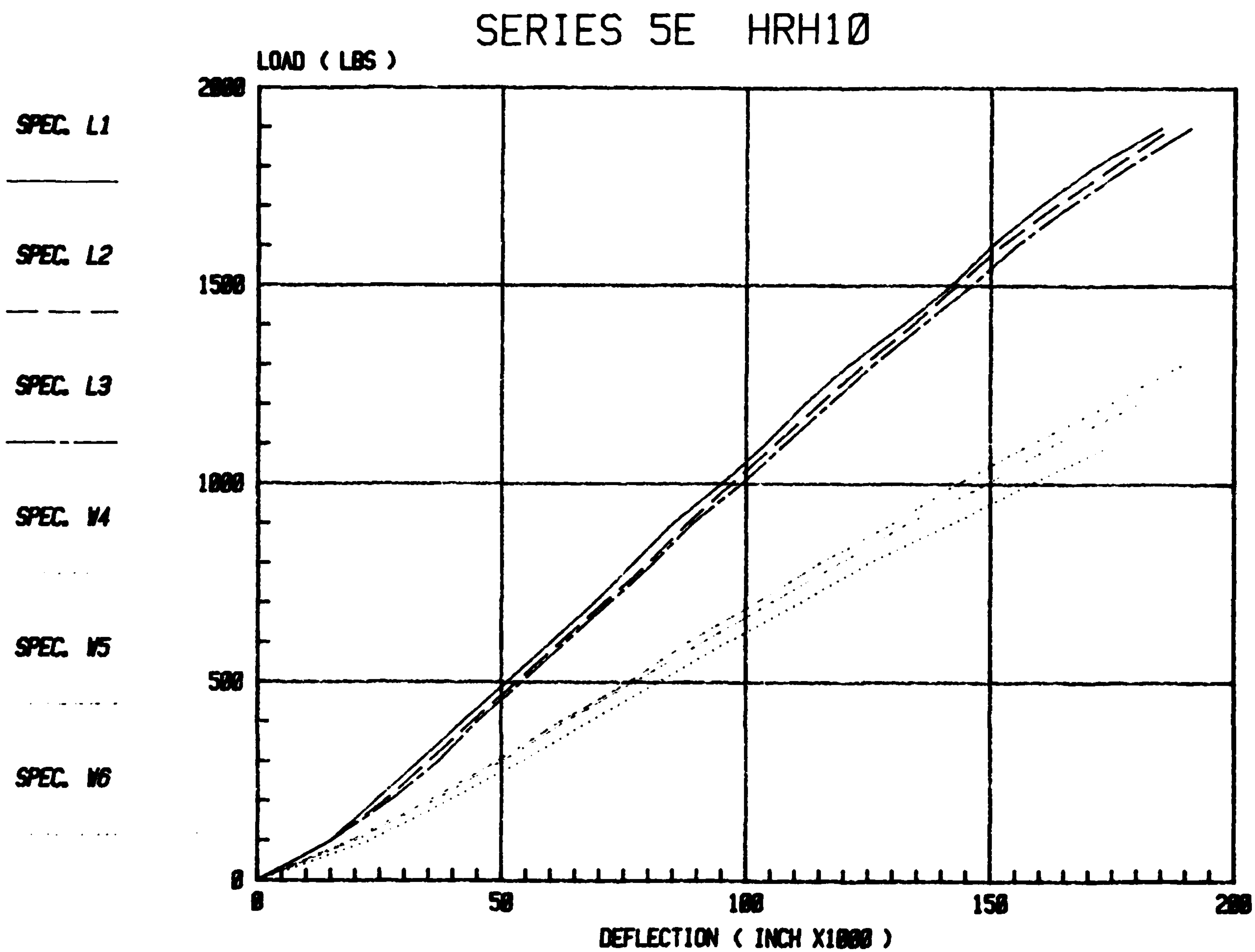


Figure A.4. Load Deflection.



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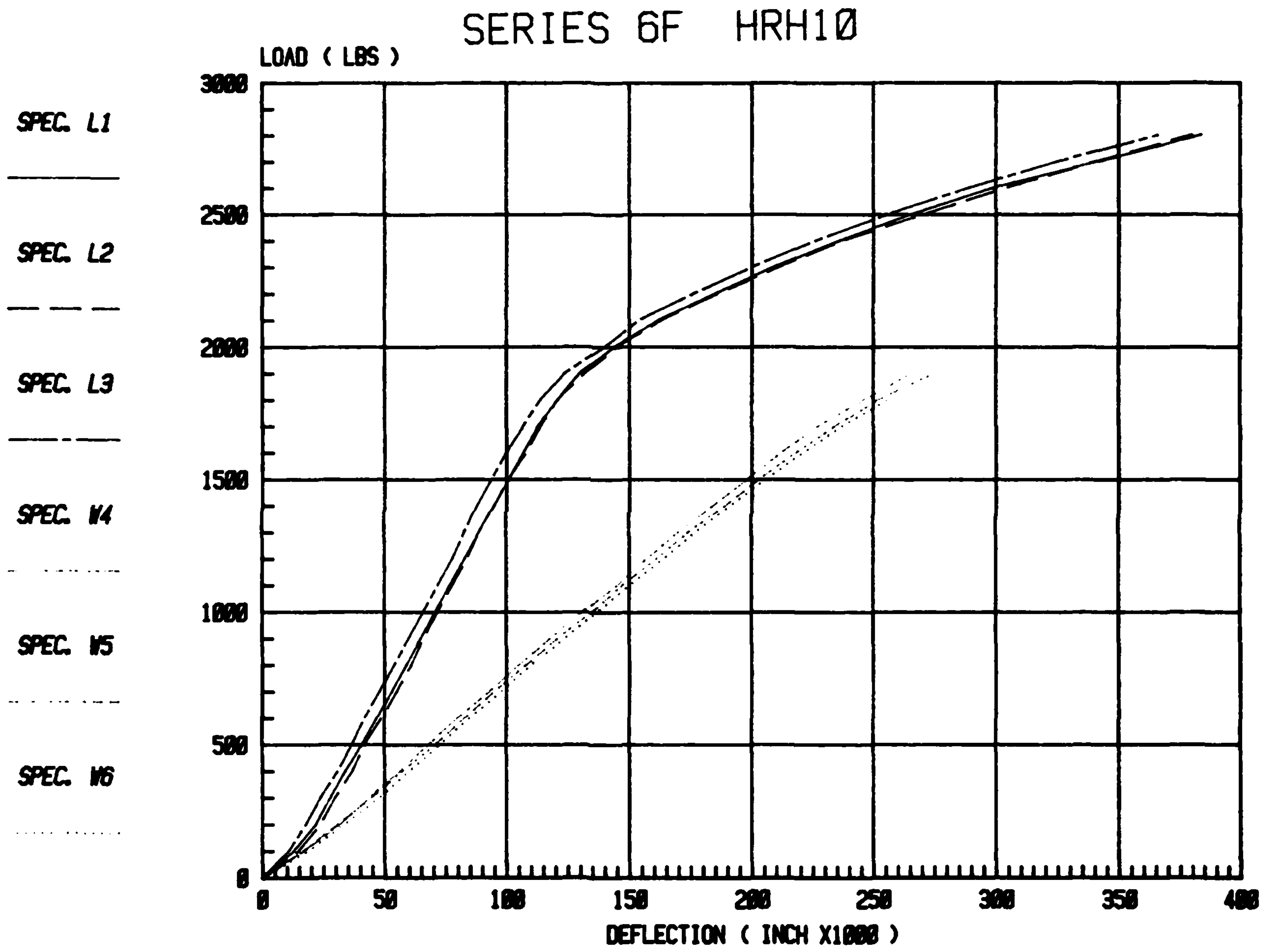
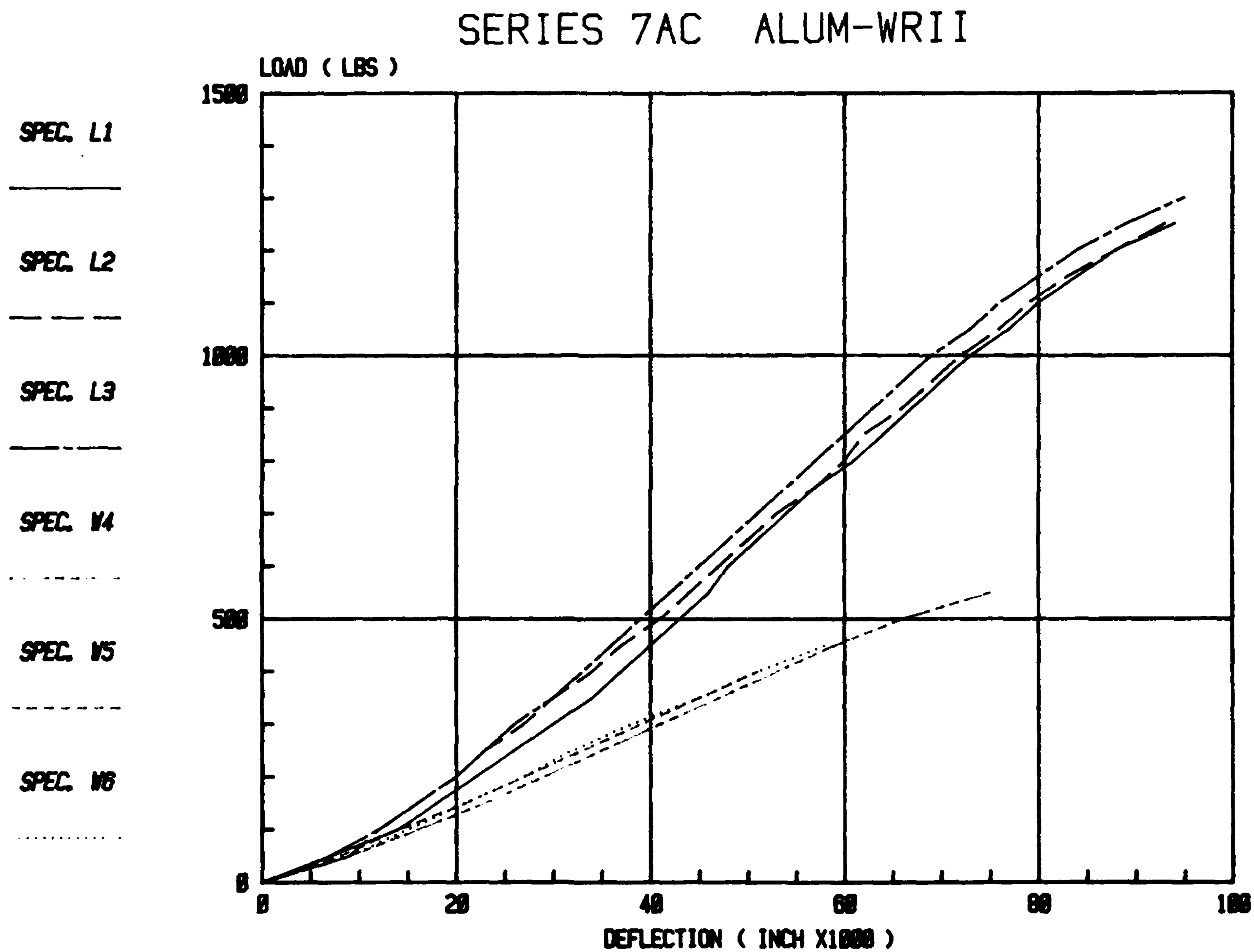


Figure A.6. Load Deflection.



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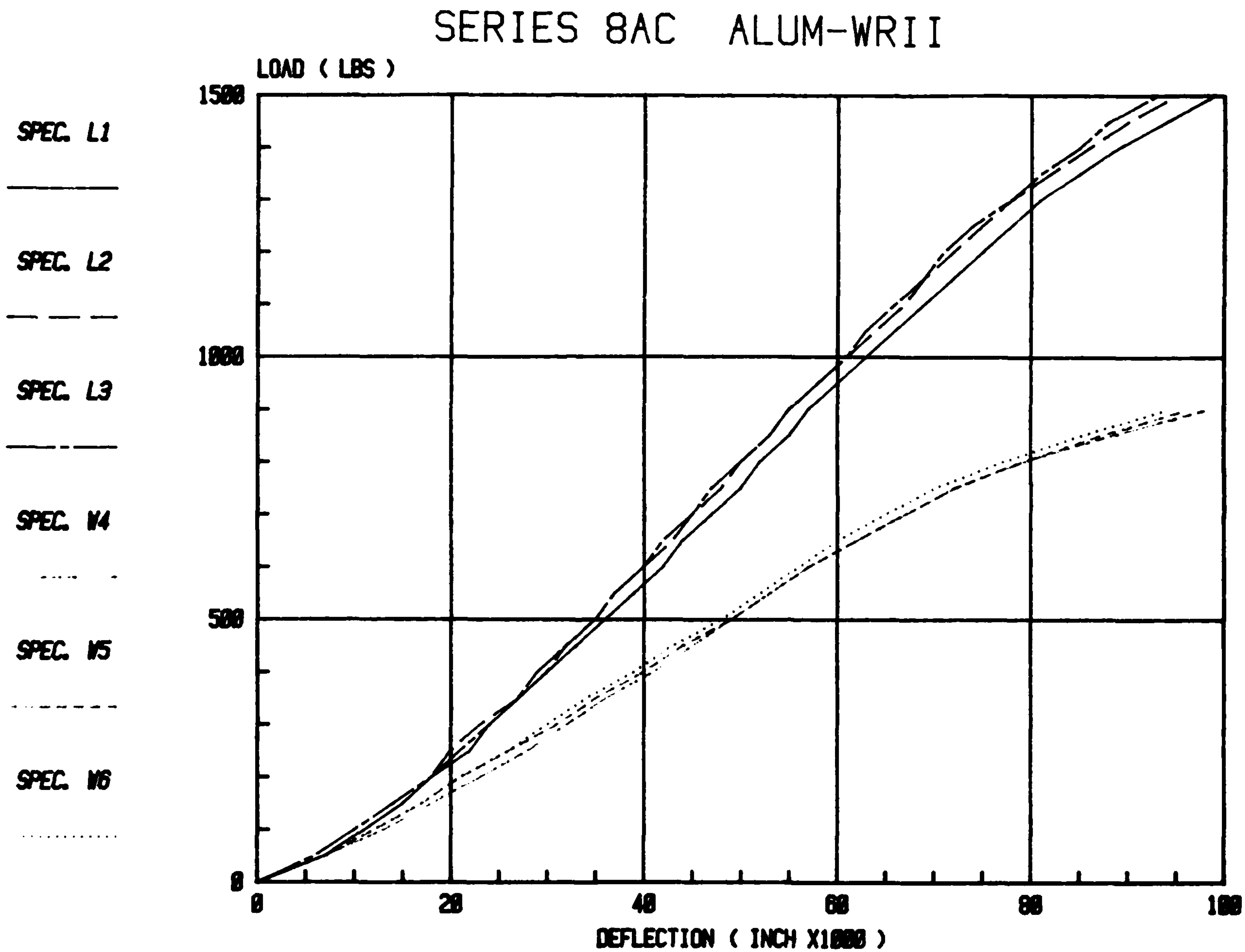

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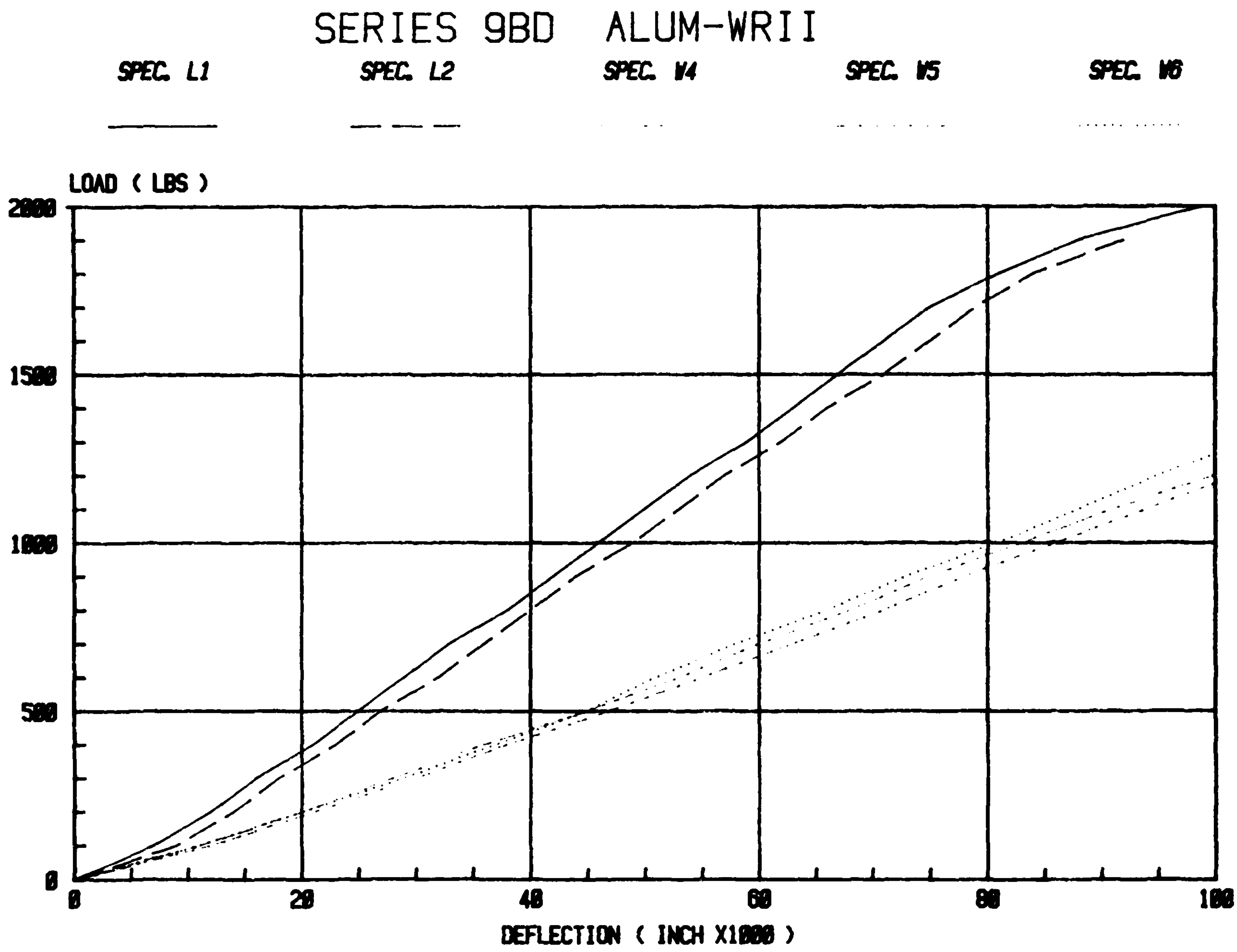


Figure A.9. Load Deflection.

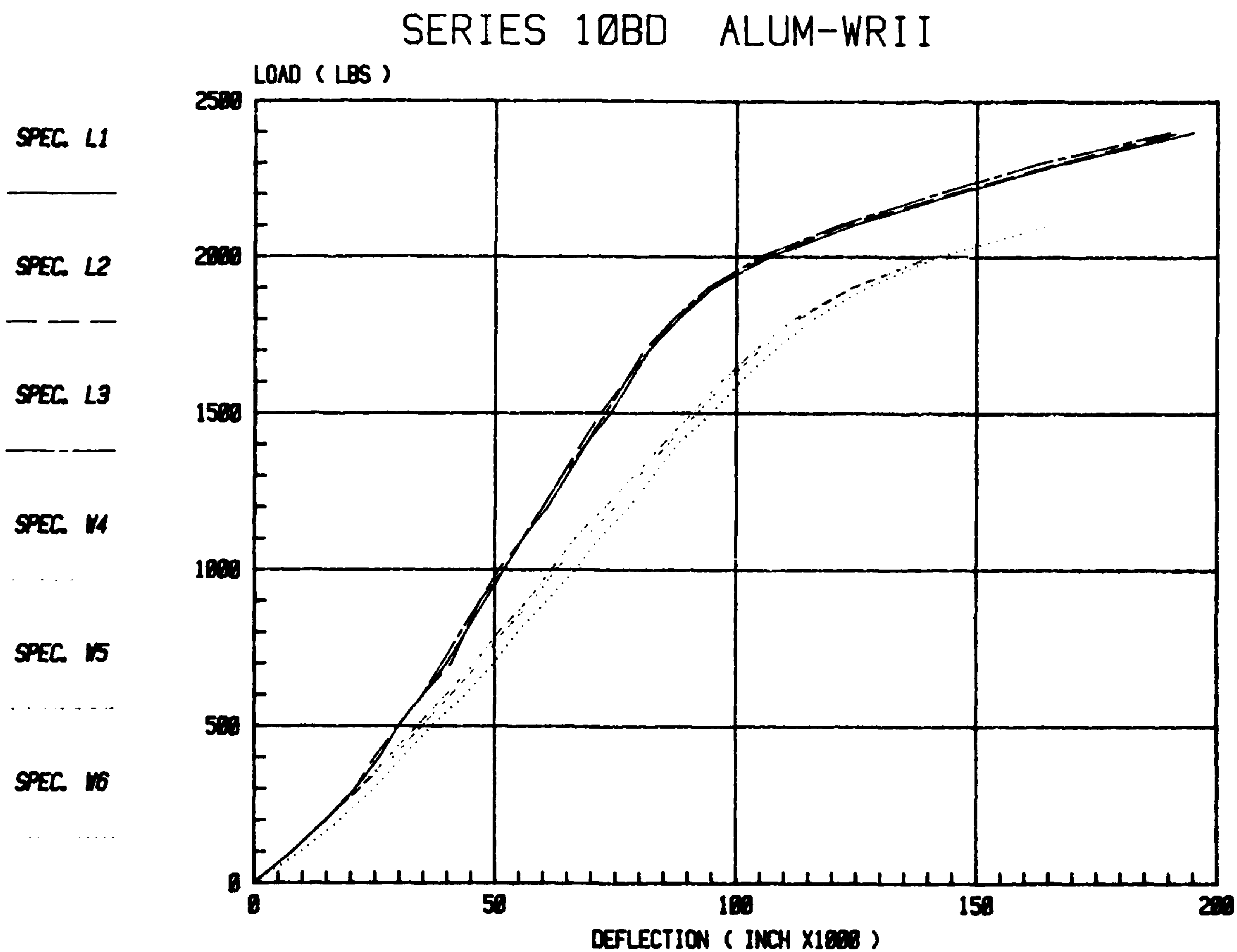


Figure A.10. Load Deflection.

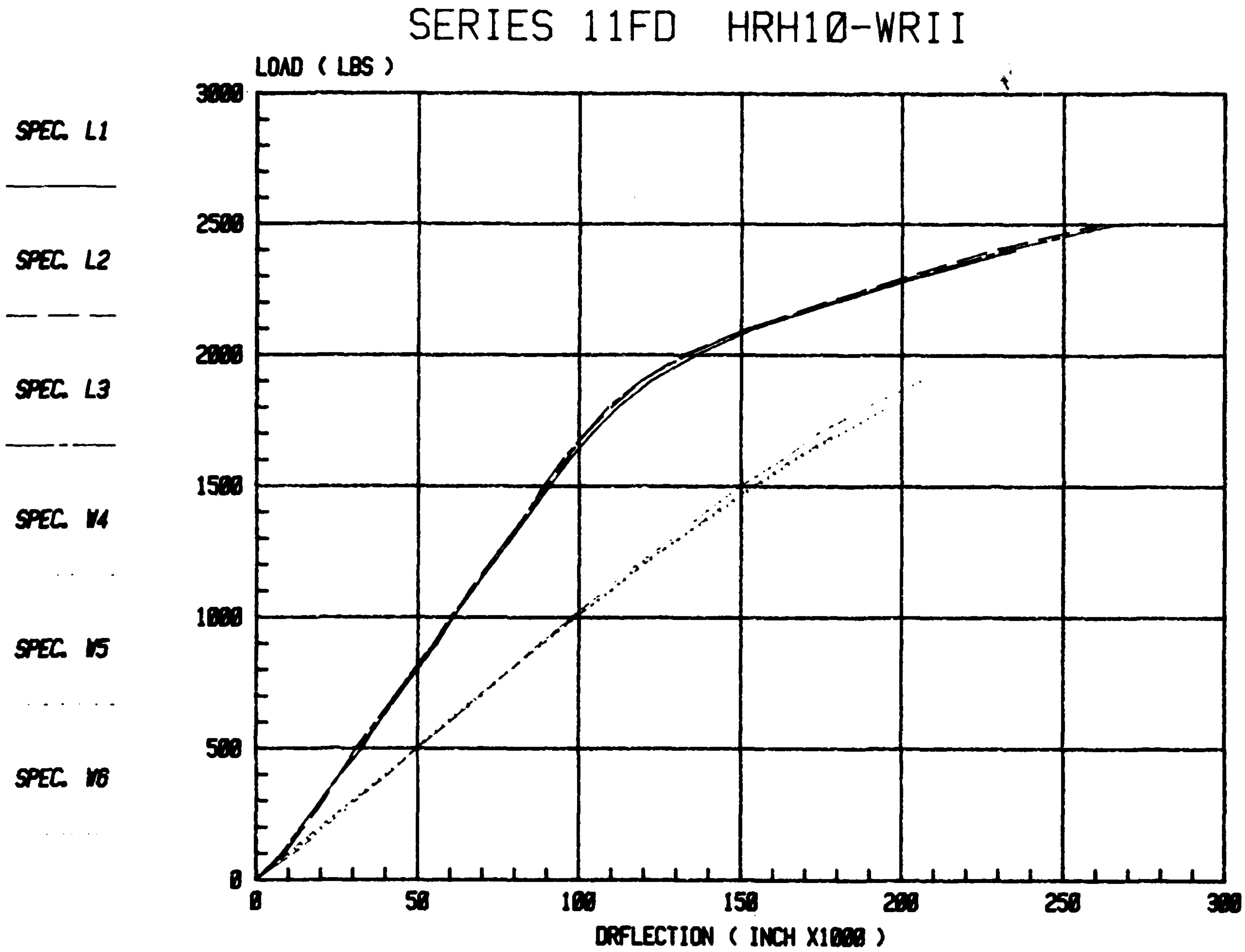


Figure A.11. Load Deflection.

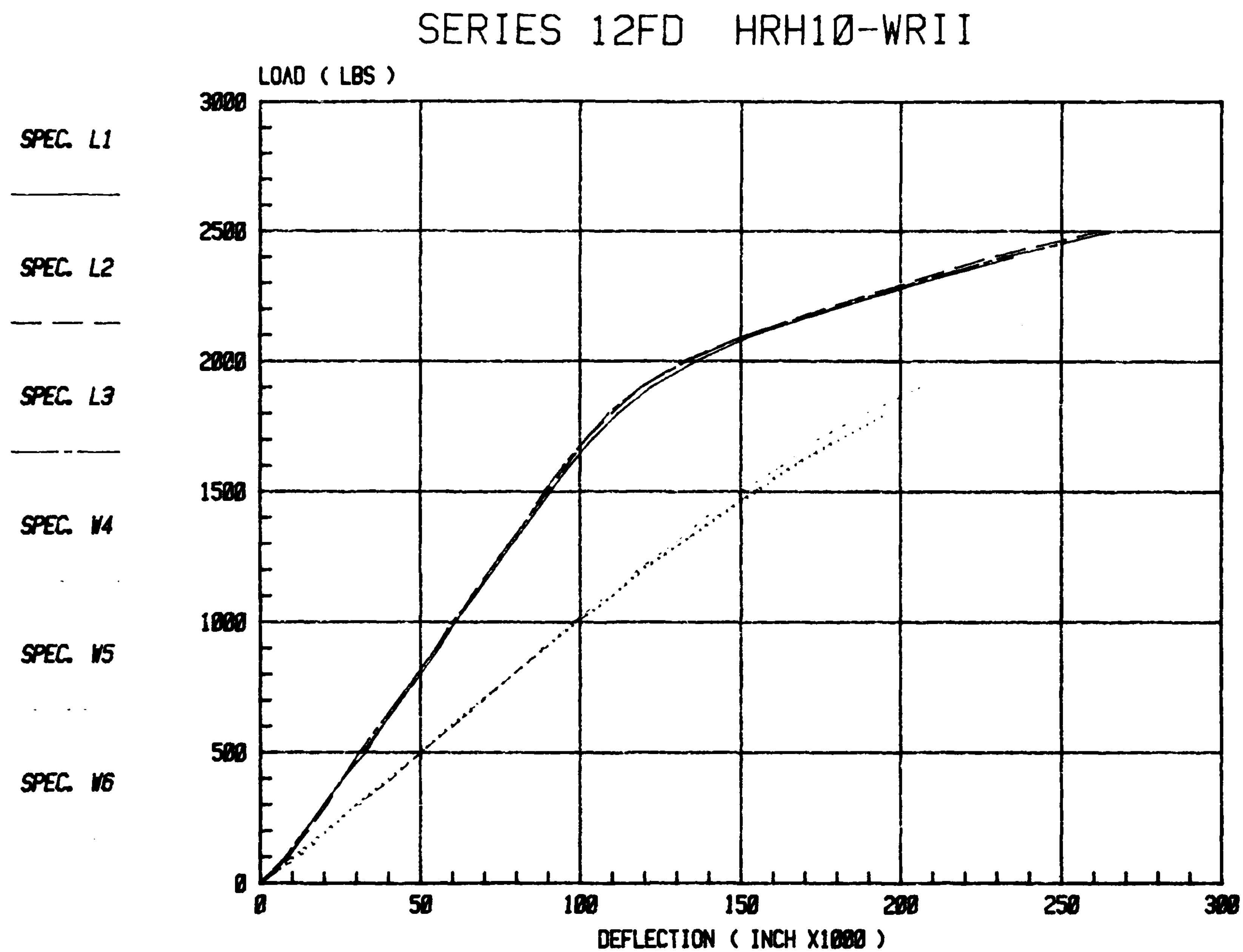


Figure A.12. Load Deflection.

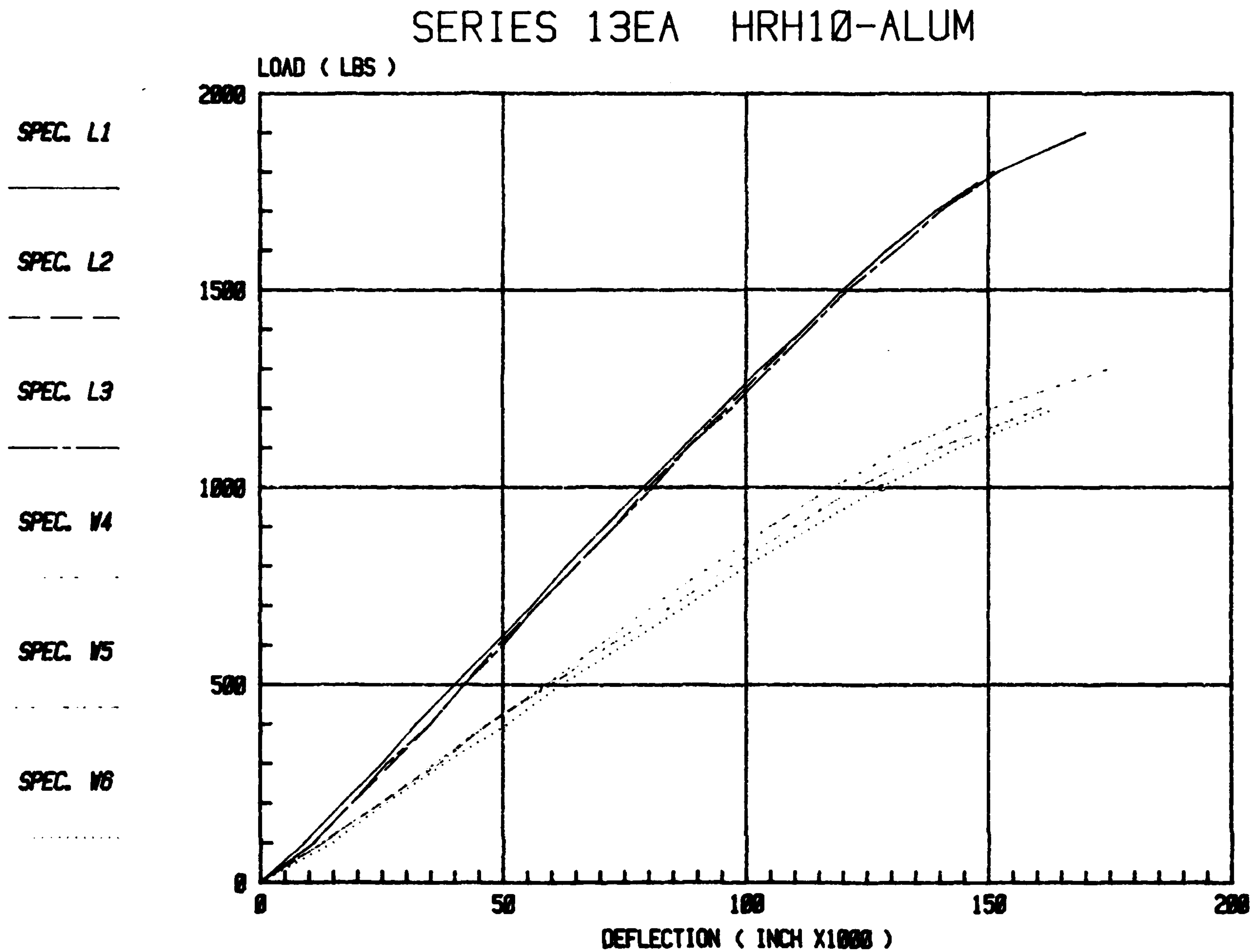


Figure A.13. Load Deflection.

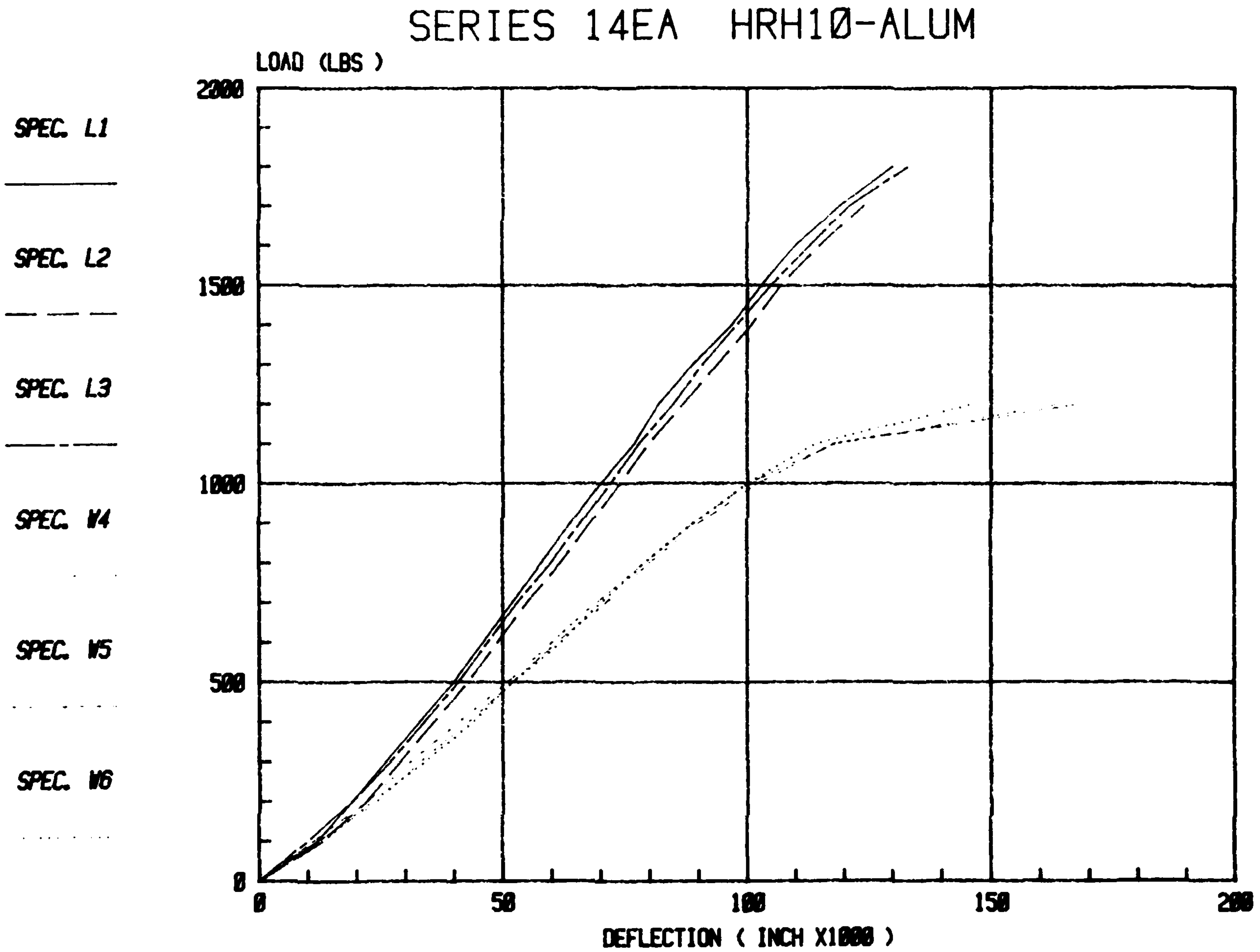


Figure A.14. Load Deflection.

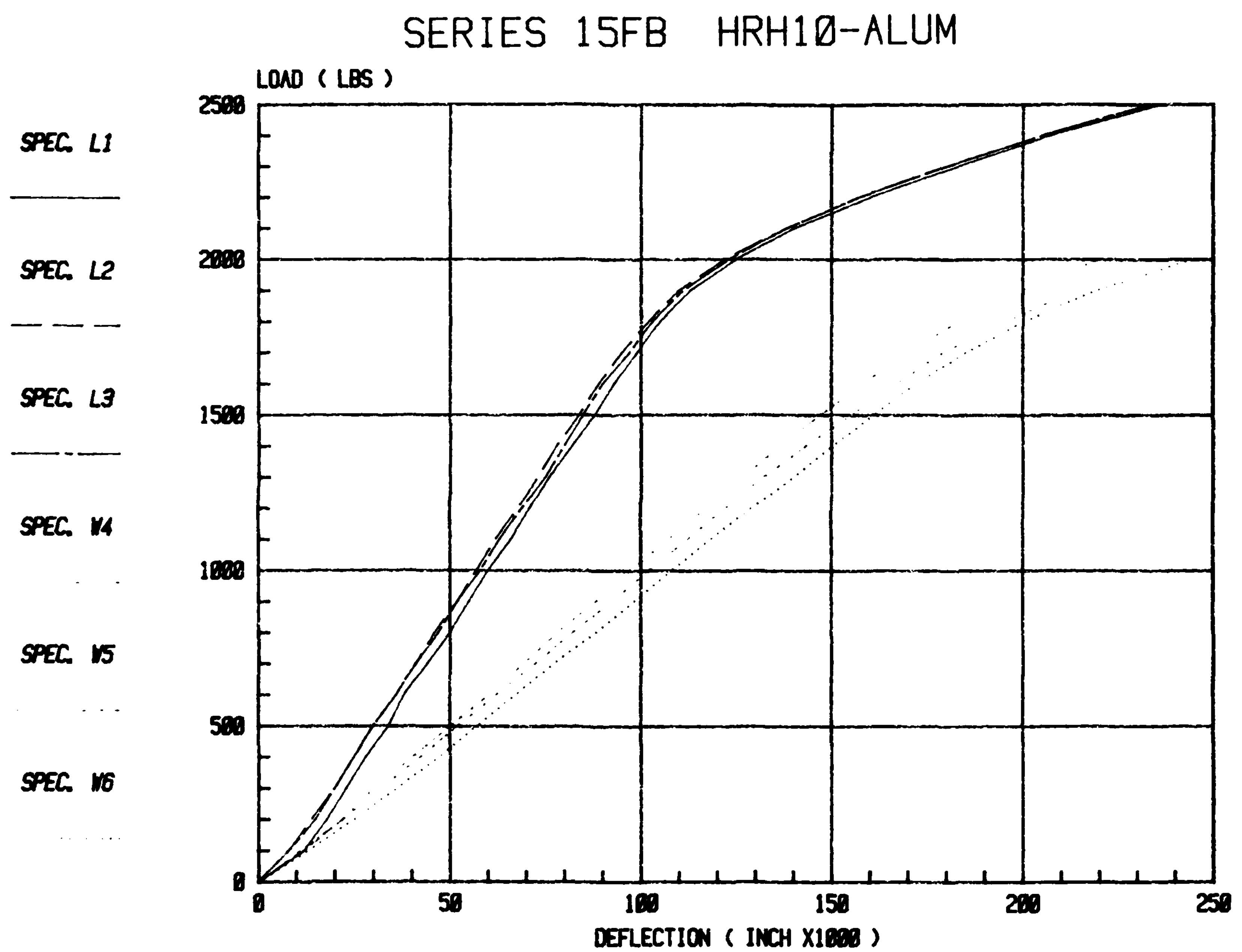


Figure A.15. Load Deflection.

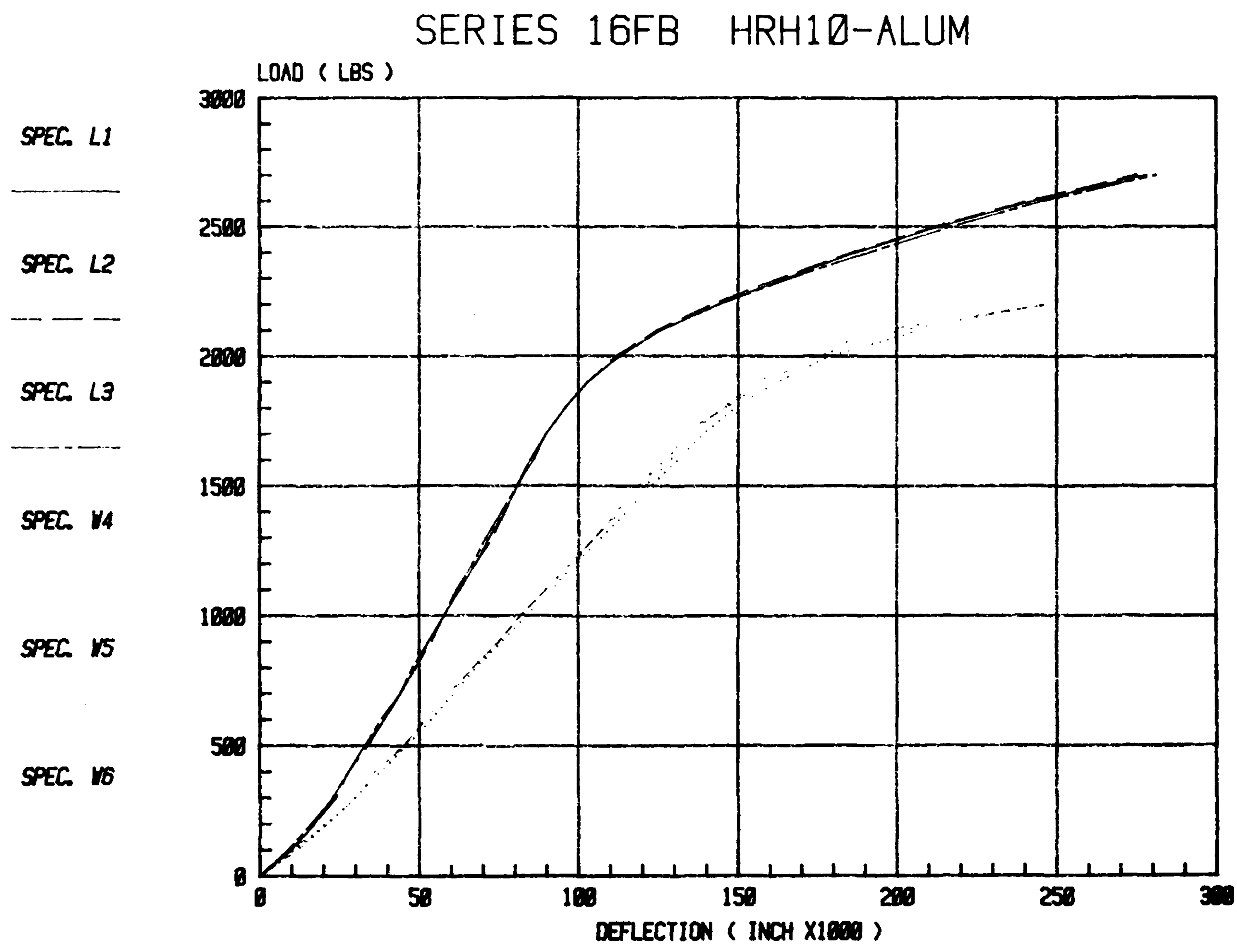


Figure A.16. Load Deflection.

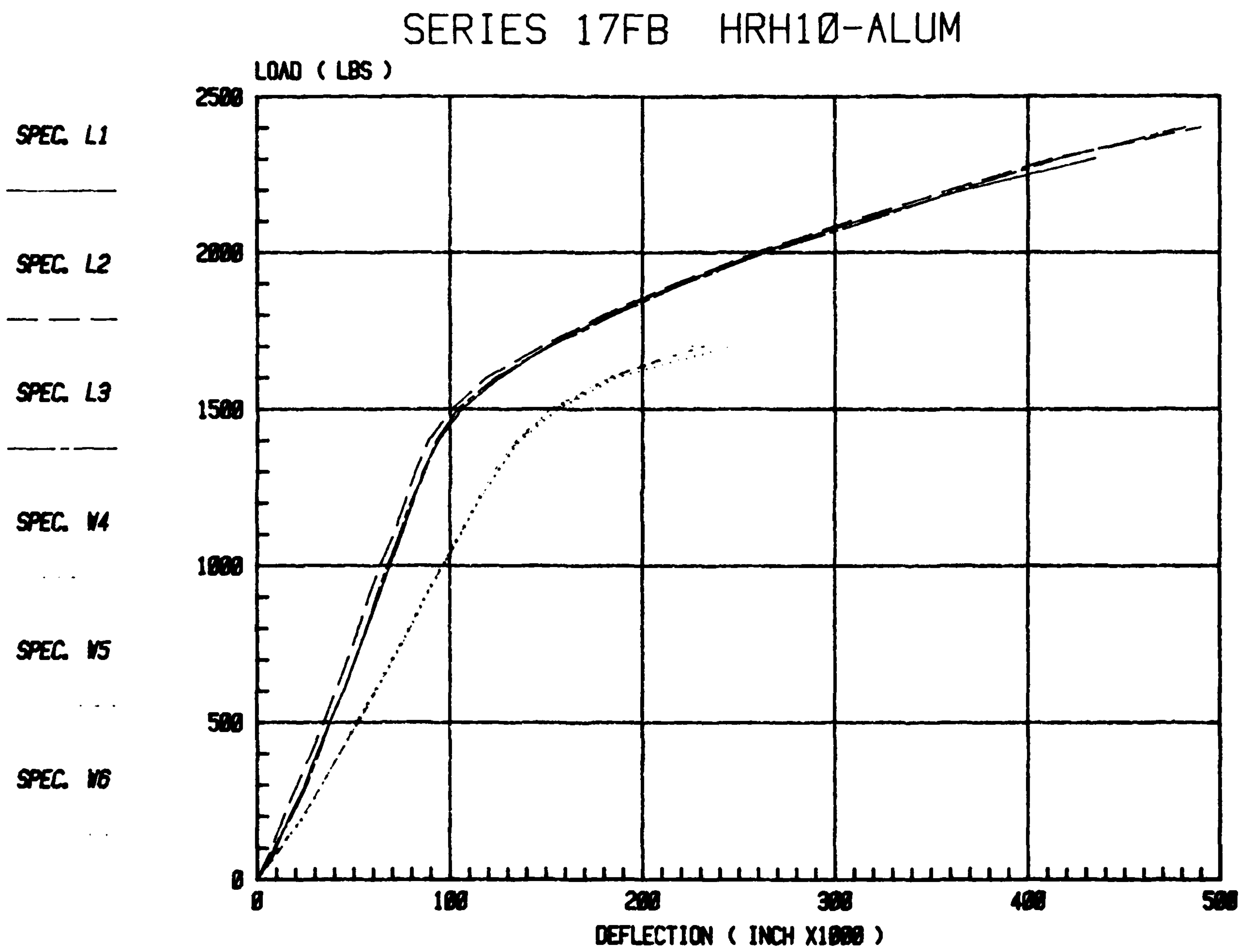


Figure A.17. Load Deflection.

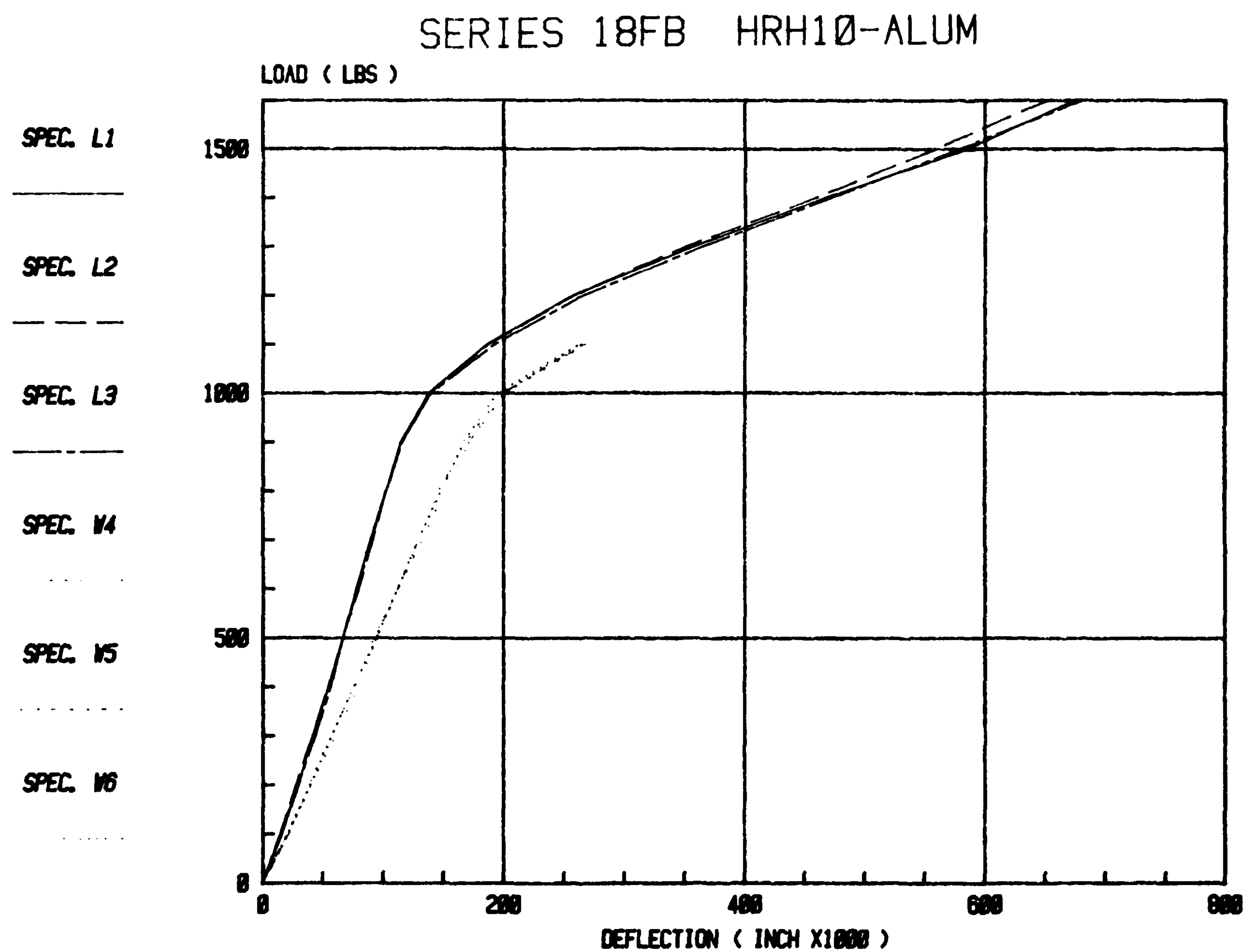


Figure A.18. Load Deflection.

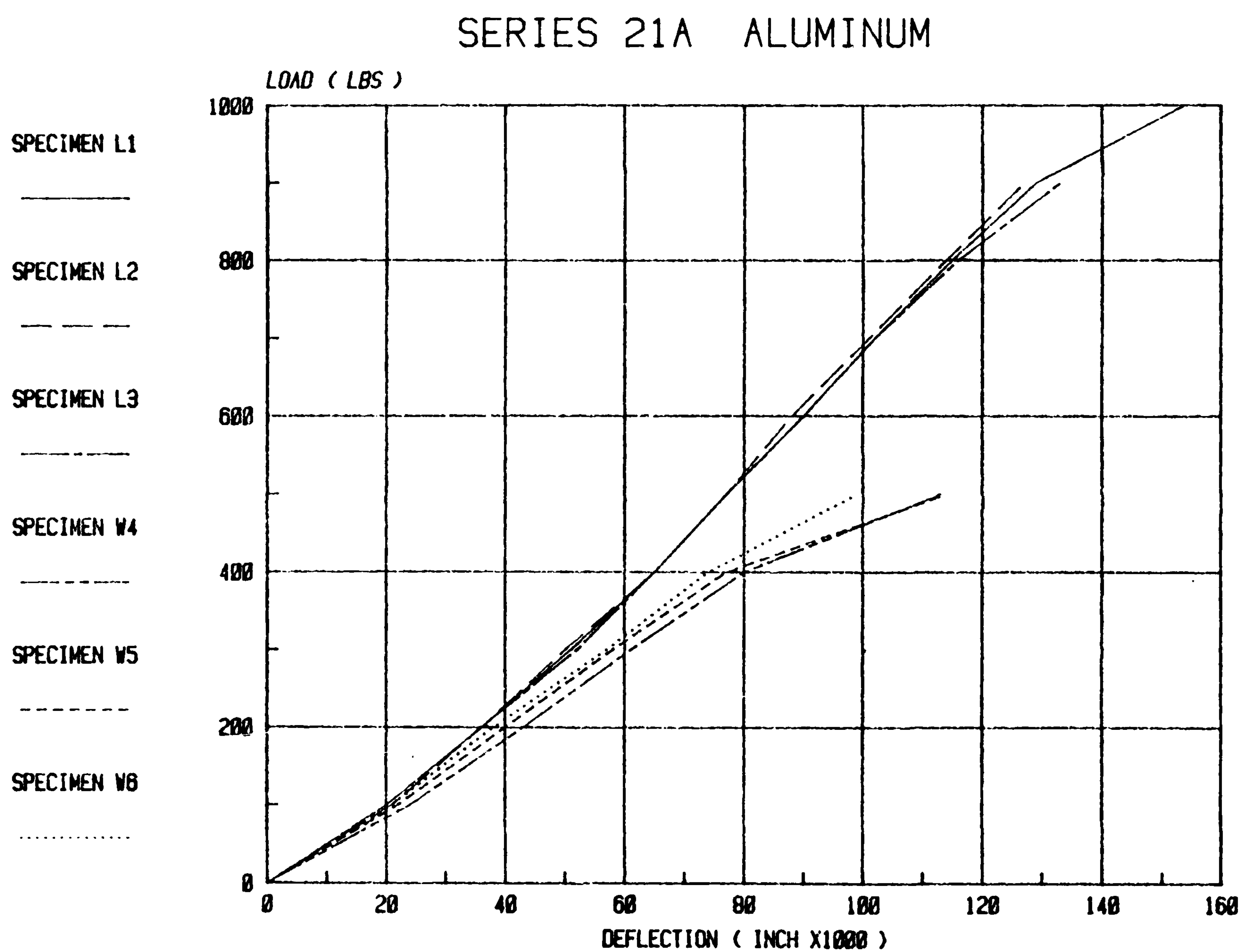


Figure A.19. Load Deflection.

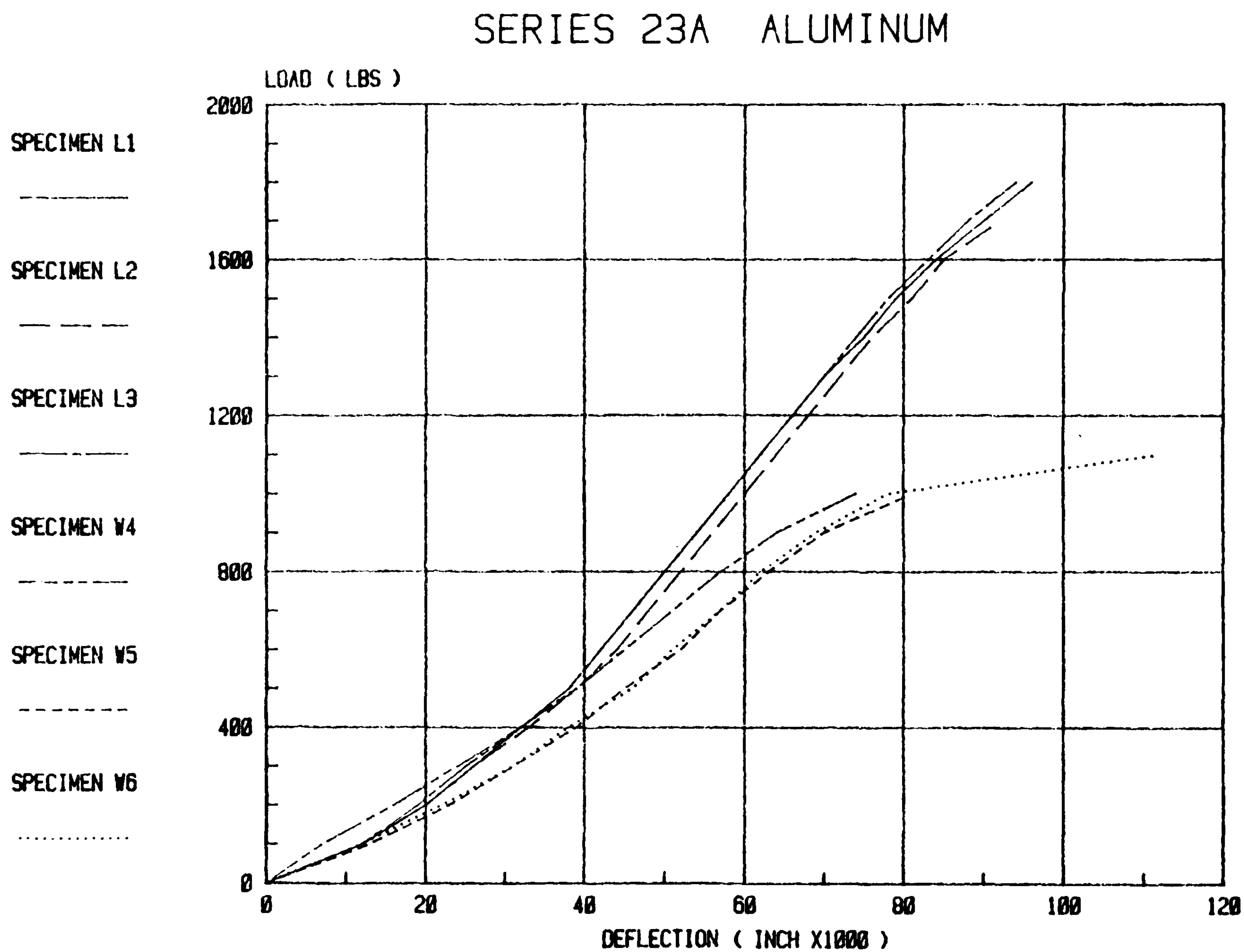


Figure A.20. Load Deflection.

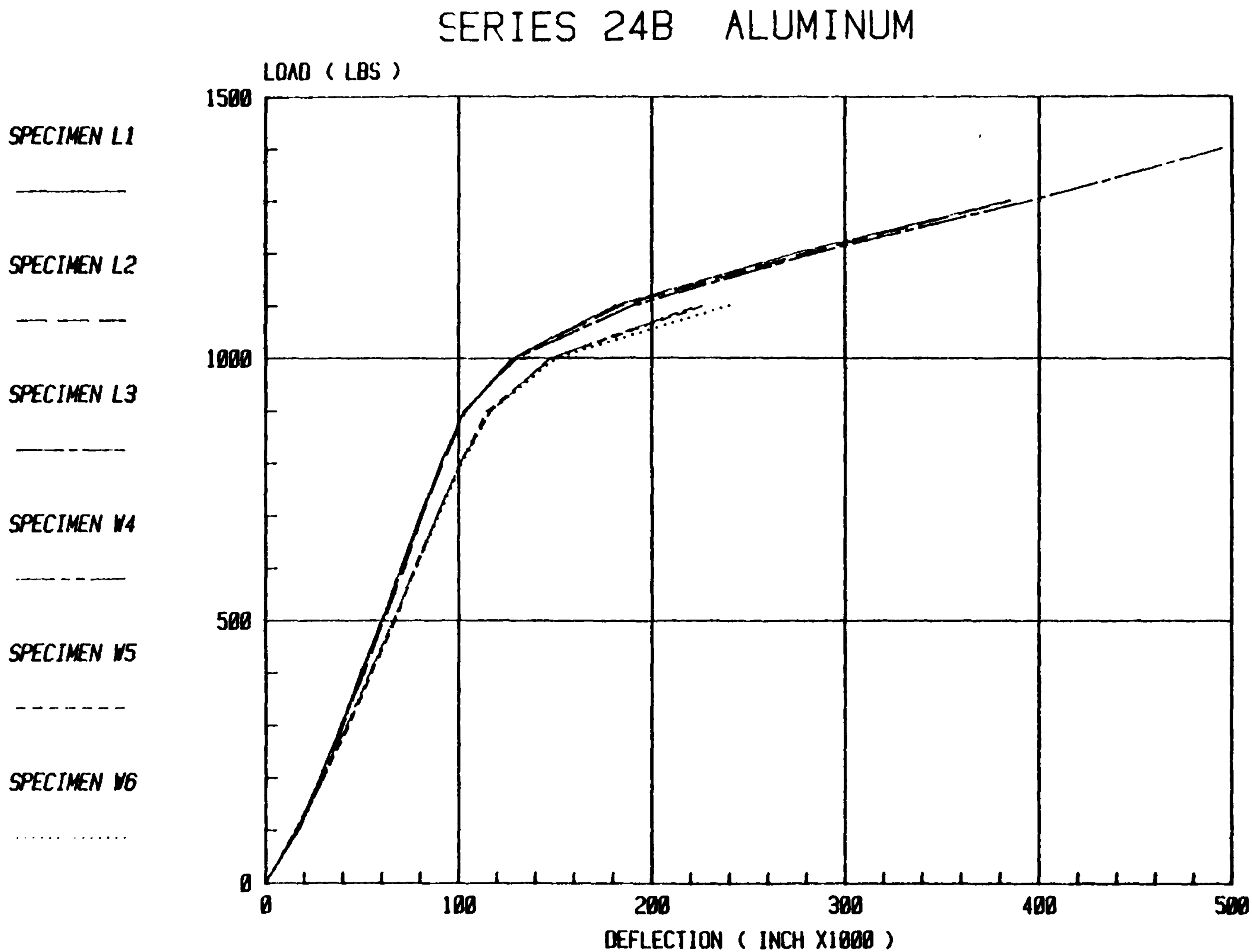
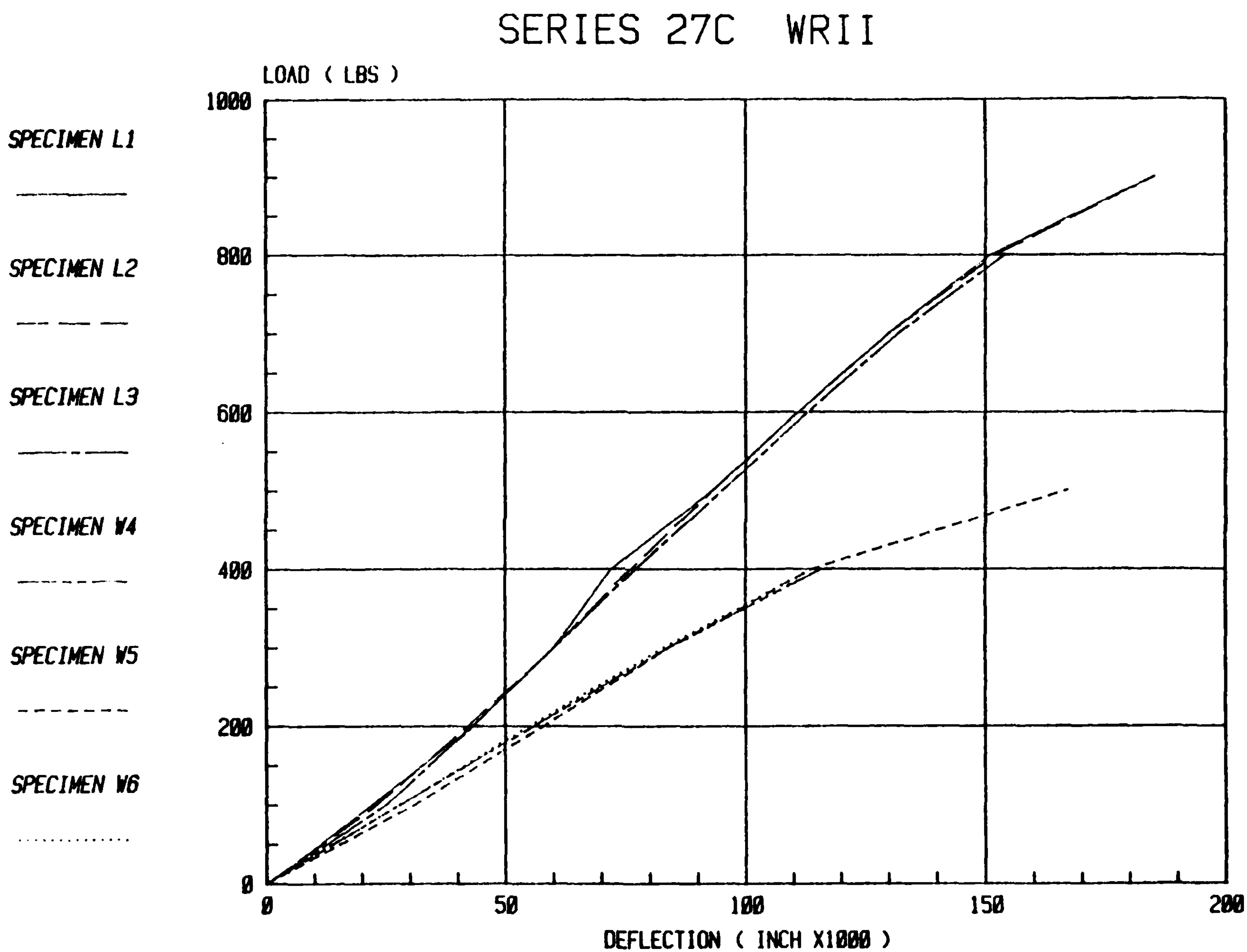


Figure A.21. Load Deflection.



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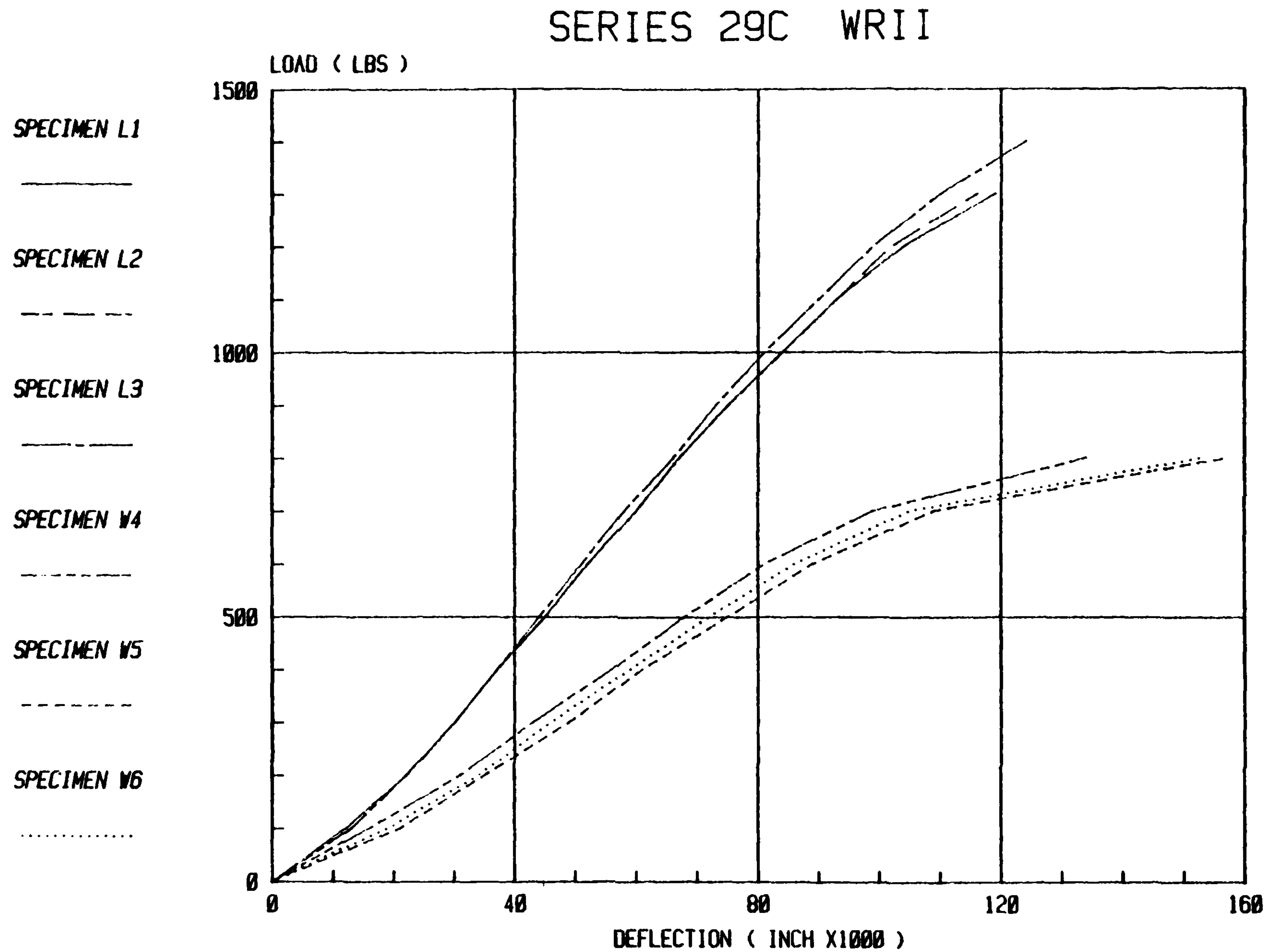

Figure A.23. Load Deflection.

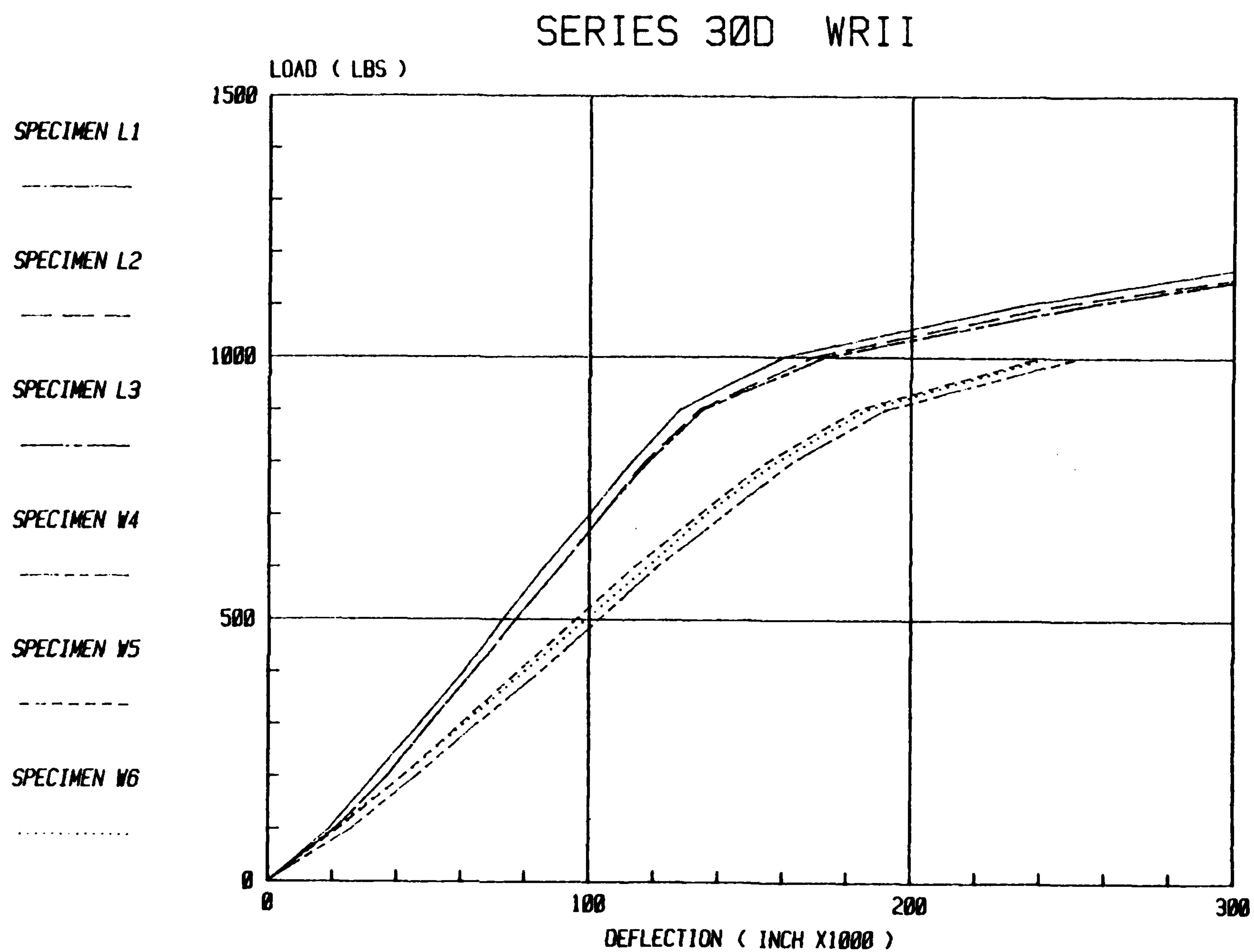

Figure A.24. Load Deflection.

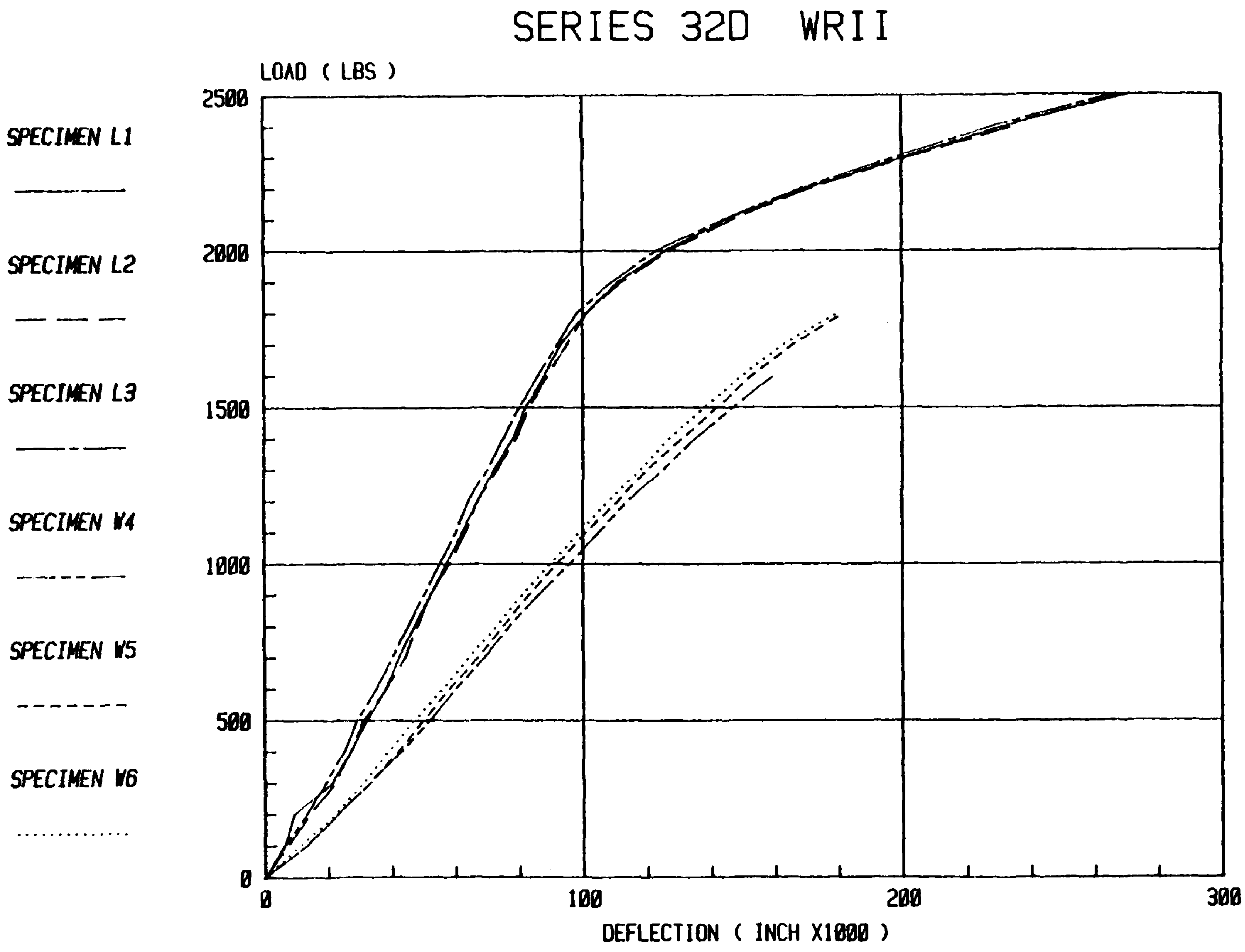

Figure A.25. Load Deflection.

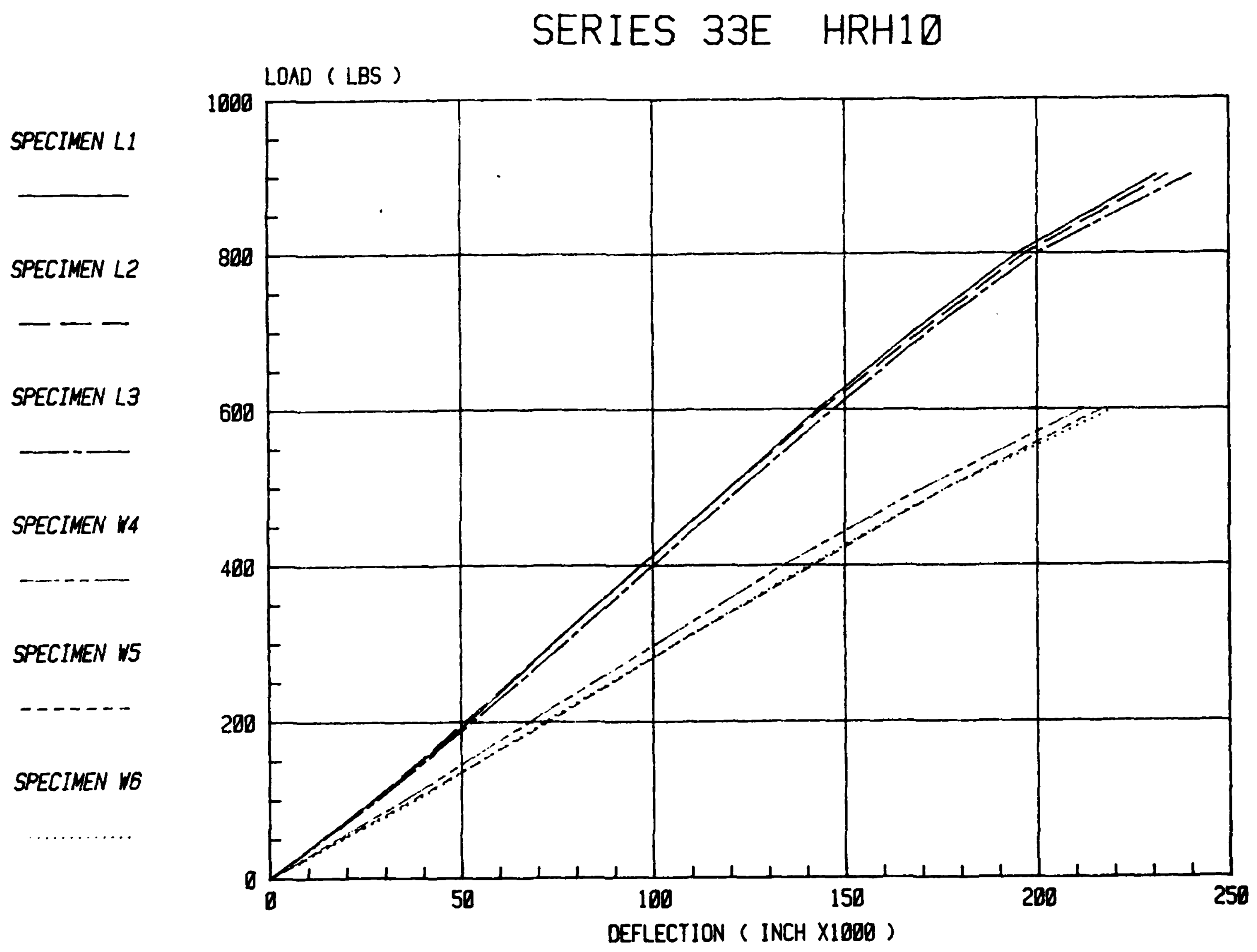

Figure A.26. Load Deflection.

AD-A160 713 EVALUATION OF A MULTI-LAYERED HONEYCOMB SANDWICH CONCEPT FOR USE IN TRANSPORTABLE SHELTERS(U) DAYTON UNIV OH RESEARCH INST J BRENTJES JAN 86 2/2

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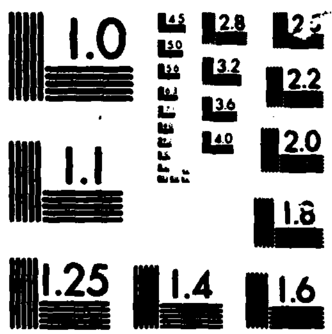

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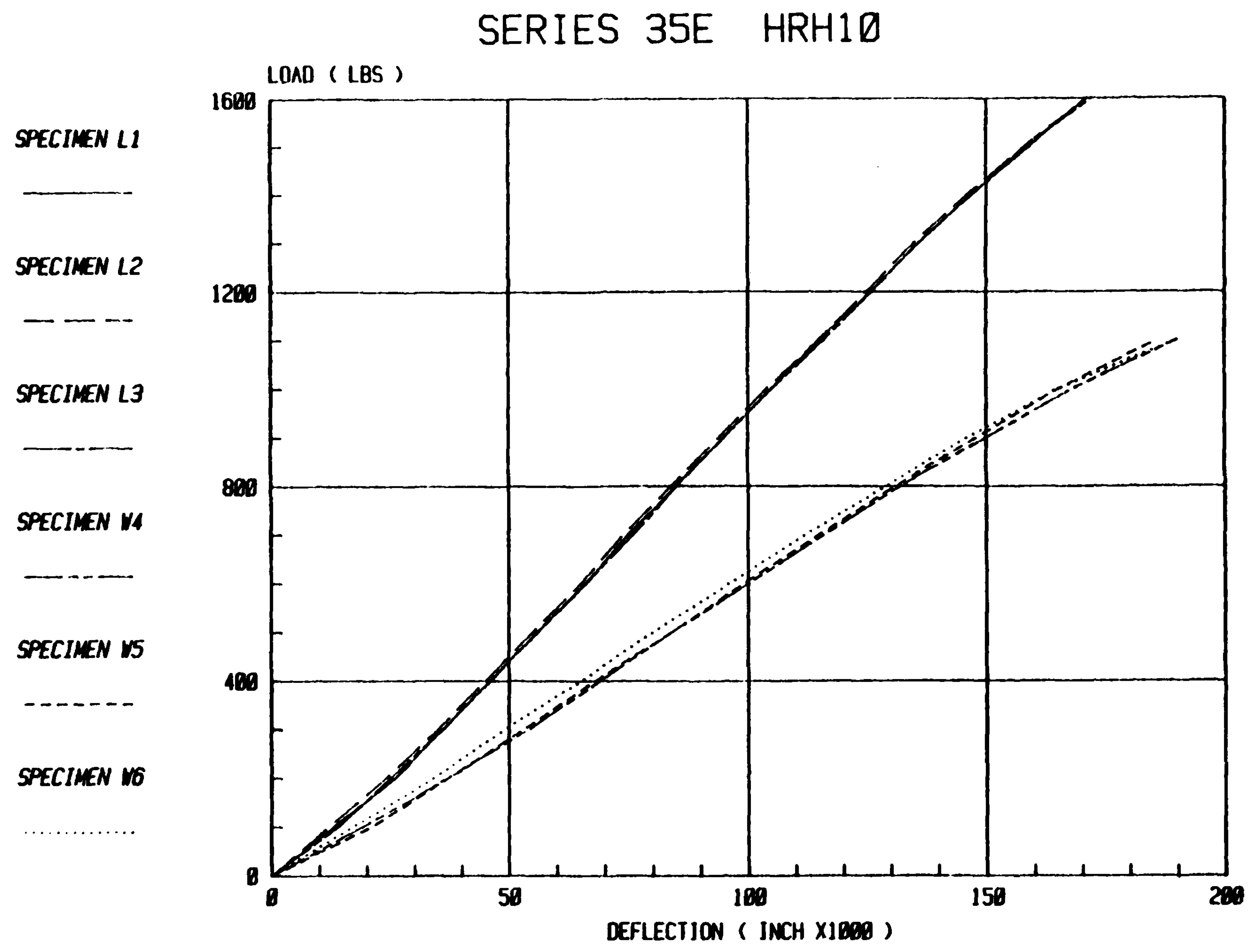

Figure A.27. Load Deflection.

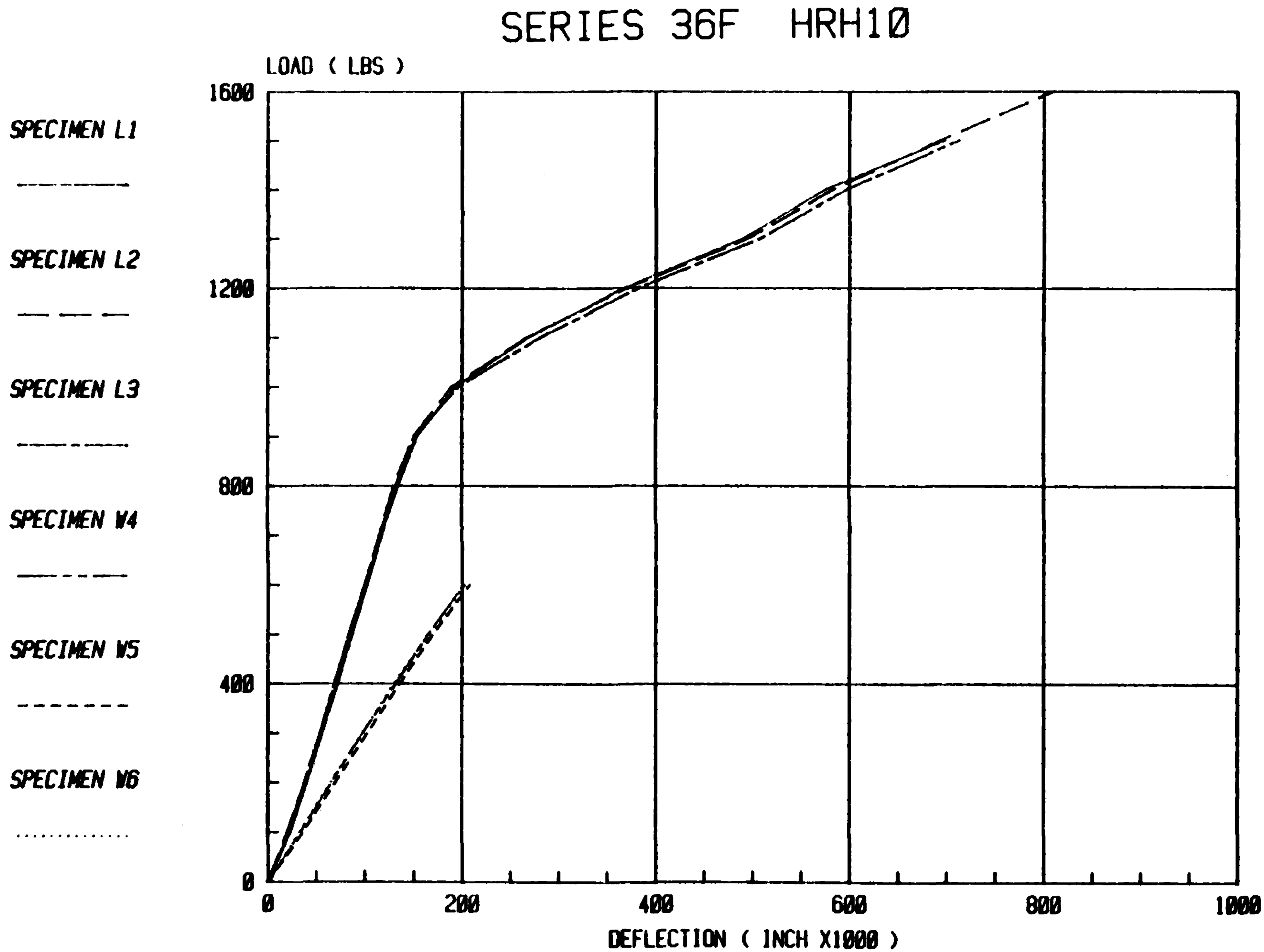

Figure A.28. Load Deflection.

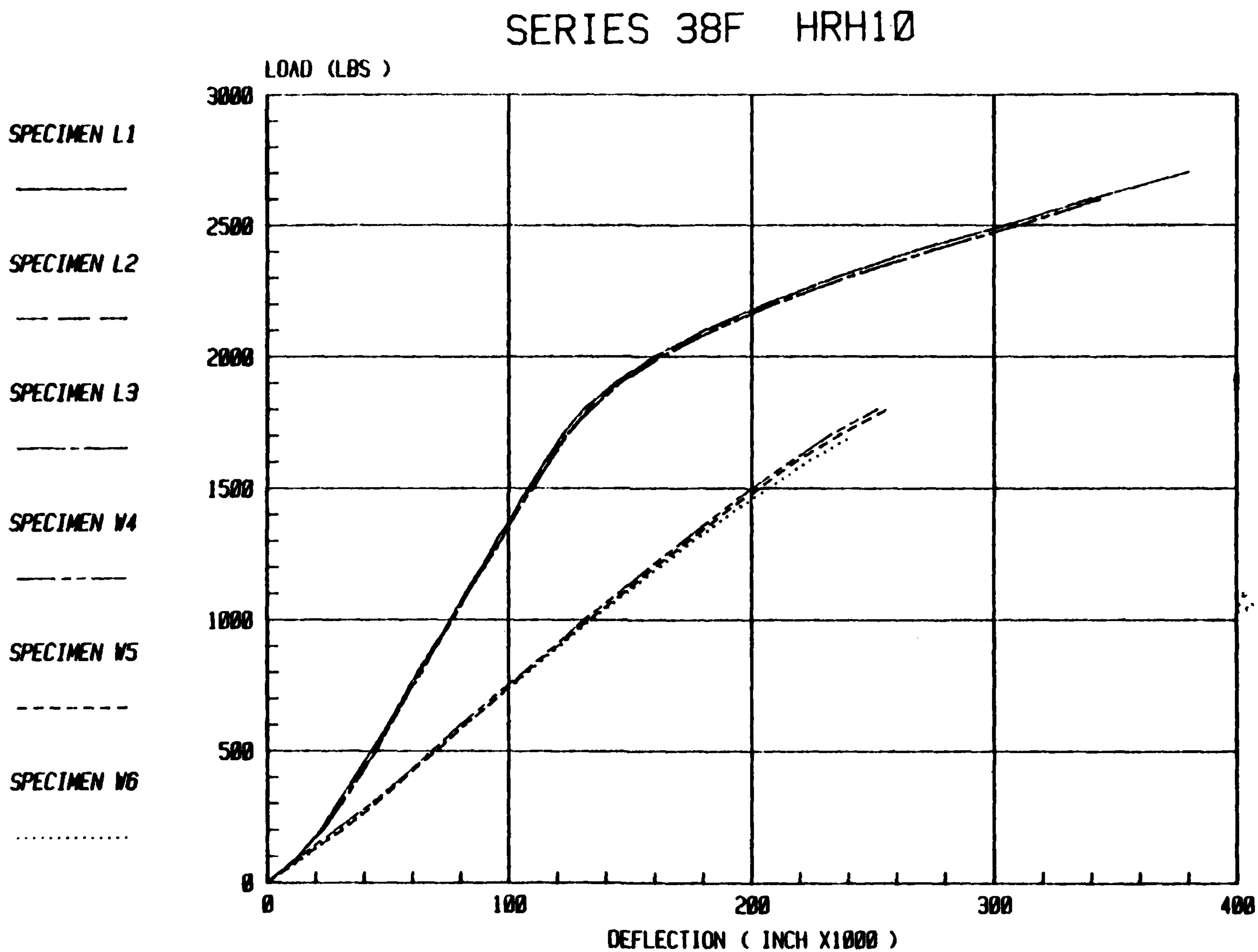

Figure A.29. Load Deflection.

APPENDIX B

EFFECT OF A RIGID SPLICE LAYER ON MULTILAYERED SANDWICH SHEAR AND COMPRESSIVE STRENGTH

A previous study of multi-layered honeycomb sandwich panels (reported in the body of this report) indicated that flatwise compressive properties were well below expected levels. The reason for this was felt to be the inability of the single ply of fiberglass/epoxy prepreg, which constituted the splice layer, to resist cut-through by the sharp core cell edges or to provide sufficiently stable cell edge support. As a result of this, it was decided to prepare some multi-layered sandwich panels which had a rigid splice layer and to test them for both flatwise compression and beam flexure properties.

Four sandwich panels were fabricated. Two consisted of four one-half inch thick layers of WRII-3/8-3.8 core and the other two consisted of four one-half inch thick layers of HRH10-1/4-4.8 core. Each panel had 0.040 inch thick 5052 aluminum serving as the outside facings. One panel of each core type was prepared with a rigid layer at each of the three splice planes and one panel of each core type was prepared with a non-rigid layer at each of the three splice planes. Table B.1 summarizes the test specimen construction. Those panels with rigid splice planes had a sheet of 0.040 inch 5052 aluminum bonded to the core at each of the three splice planes. Those panels with non-rigid splice planes had a single ply of EA9601NW adhesive film at each of the three splice planes. The facings and aluminum splice layers were bonded to the core with EA9601NW adhesive film.

The panels were cut into 16 inch long by 3 inch wide specimens for beam flexure testing (see Figure 2). When the flexure test was completed, two 3 inch by 3 inch specimens were cut from each long specimen for compression tests.

The flexure specimens failed with an apparently clean transfer of shear stress from one layer to the next. Figure B.1

TABLE B.1

SUMMARY OF TEST SPECIMEN CONSTRUCTION

Outside Facing	Core Composition	Splice Plane Composition
0.040" 5052 Alum.	4 layers of 1/2" WRII-3/8-3.8	0.040" 5052 Alum. bonded with EA9601 NW - RIGID
"	"	1 ply EA9601 NW - NONRIGID
"	4 layers of 1/2" HRH10-1/4-4.8	0.040" 5052 Alum. bonded with EA9601 NW - RIGID
"	"	1 ply EA9601 NW - NONRIGID

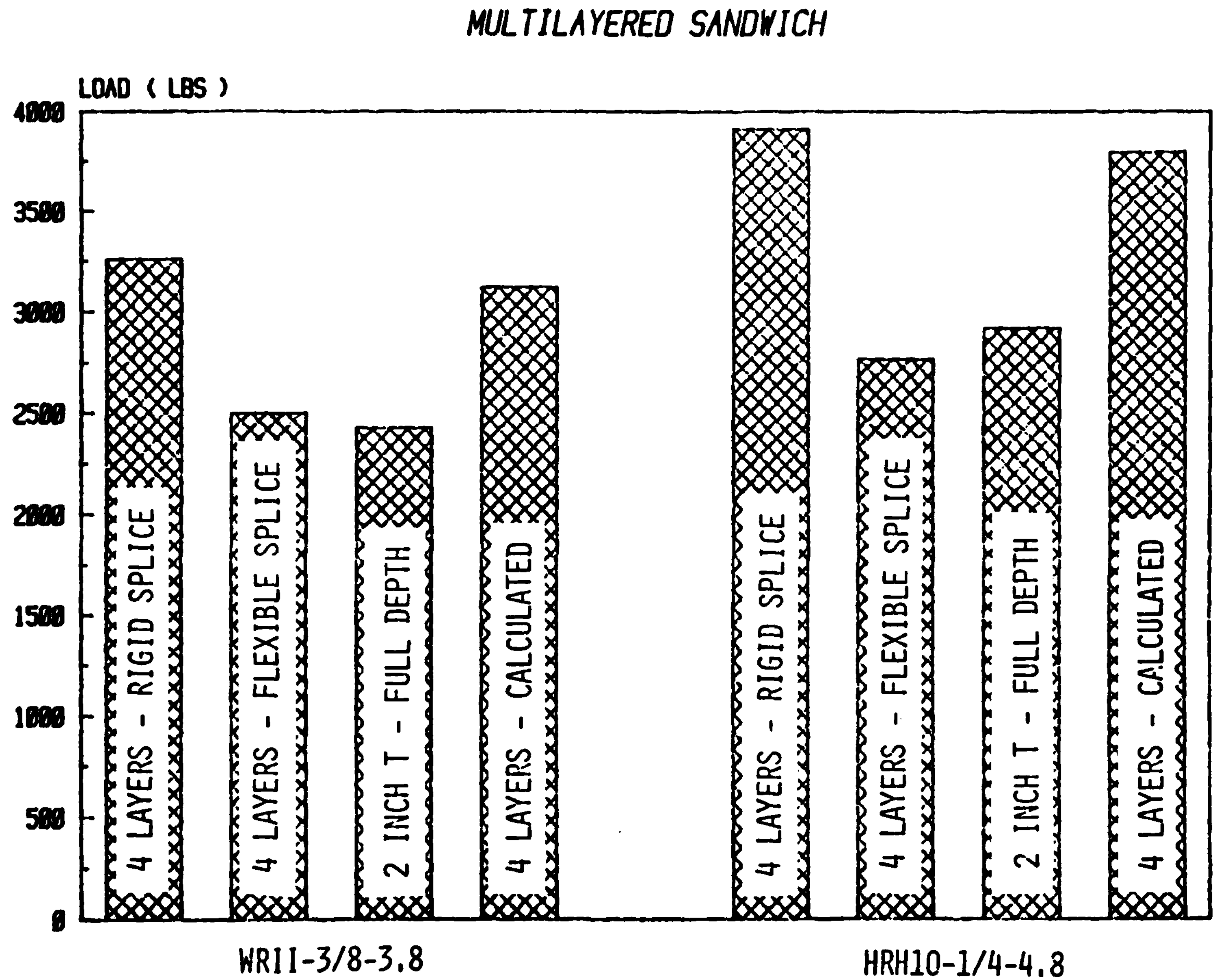

Figure B.1. Beam Flexure Load at Failure.

illustrates the beam flexure results obtained for four-layered sandwich with both rigid and non-rigid splice layers and with full depth sandwich. It is evident that the load at failure is considerably higher, for both core types, for the specimens with the rigid splice layers. The calculated values illustrated in Figure B.1 are based on the core shear strength levels achievable with one-half inch thick core. Thus, it appears that the advantage of higher shear strength available from thinner core is realized in the multi-layered sandwich constructions.

The flatwise compression results are illustrated in Figure B.2. It is evident that the four-layer sandwich construction with rigid splice layers provide a higher compressive strength than either 0.5 inch or 2.0 inch full depth core. This is in marked contrast to results obtained for a non-rigid splice layer (Table 10 and Figure 27) in which case the strength of the multi-layered constructions was only about 60 percent that of the full depth construction. This dramatic difference is probably due to the resistance of the *rigid* splice layer to cut-through by the sharp cell edges and to a higher level of stabilization provided to the cell edges bonded to this rigid layer.

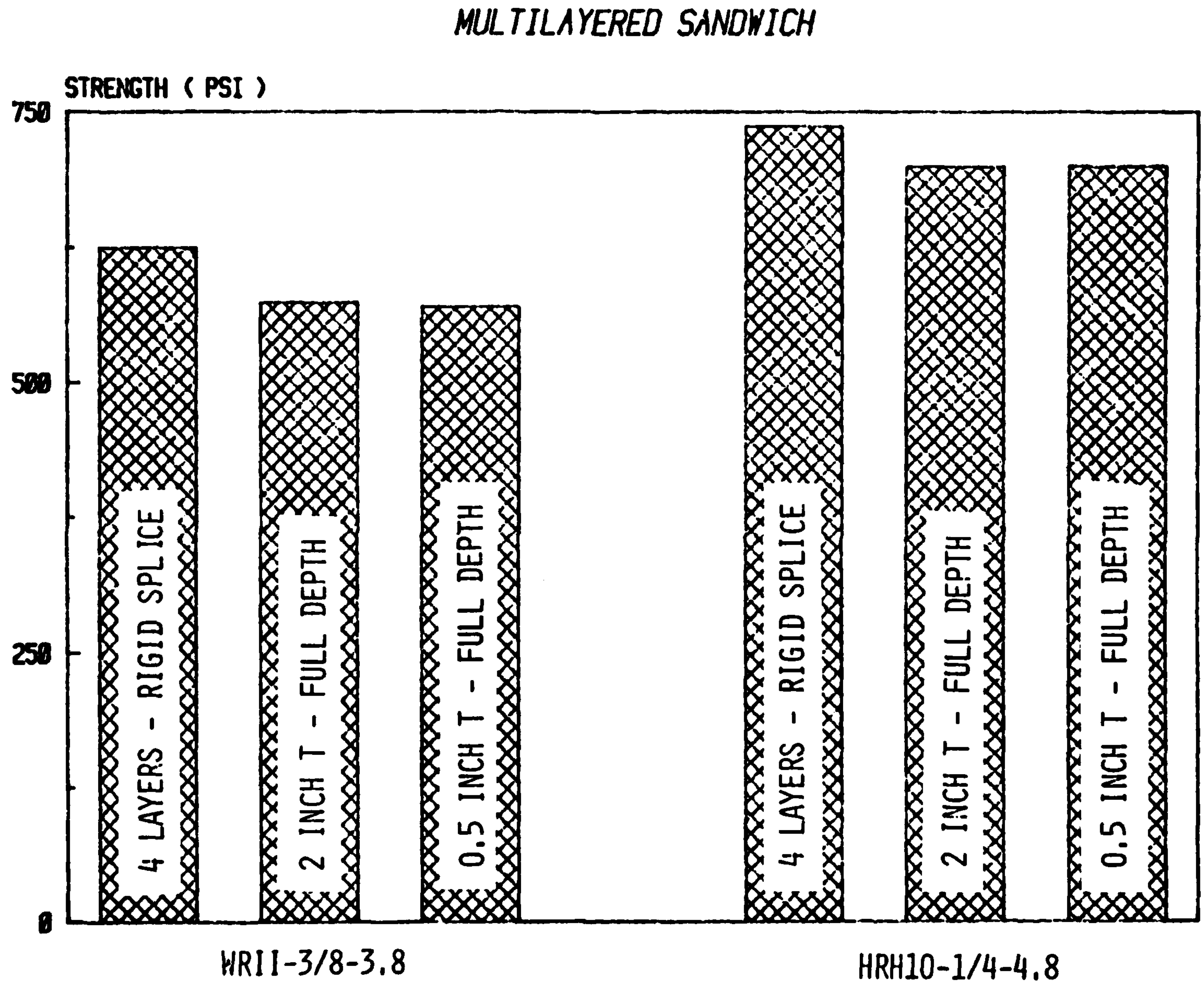

Figure B.2. Compressive Strength.

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